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DIASTROPHISM AND THE FORMATIVE PROCESSES

XIII. THE BEARINGS OF THE SIZE AND RATE OF INFALL OF PLANETESIMALS ON THE MOLTEN OR SOLID STATE OF THE EARTH

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In the last article of this series[1] it was found (1) that the solar gases, as they were expelled to form the planetary systems, were so mixed that they were unfitted to form solid bodies such as the terrestrial planets, the planetoids, and the satellites, until after they had been sifted by a selective process, (2) that the sifting process introduced such a serious departure from familiar modes of gaseous condensation as to require reinterpretation, (3) that the process of concentration was also complicated by inherited motions, (4) that it was still further conditioned by the formation of precipitates and precipitate aggregates, and (5) that the planetary cores, while in process of formation, were subjected to viselike squeezing, more intense below than above, followed by partial relaxation, so that selective extrusion attended the closing processes, involving the ascent of the lighter mobile matter and the compression and reorganization of the rest, thus contributing

[1] "Diastrophism and the Formative Processes. XII. The Physical States of the Planetary Nuclei during Their Formative Stages," *Jour. Geol.*, Vol. XXVIII (1920), pp. 473–504.

toward high density, rigidity, and elasticity in the central parts. It was further found that the shapes of the planetary cores were influenced from the very outset by the gyratory system of circulation that attended their formation, and that they thus failed to take on strictly spherical forms, so that they were likely to yield unsymmetrically to the heavy masses later built upon them by planetesimal growth. Even the primitive circulation thus had its influence on the diastrophism that developed much later.

Let us now consider the planetesimal growth. This involves (1) a study of the nature of the planetesimals at the start, (2) the conditions that affected the mode and extent of their growth, and (3) the modes and rates of their infall and the effects of these on the molten or solid state of the earth, as also on its content of explosive gases.

THE NATURE OF THE PLANETESIMALS AT THE START

The way in which the planetesimals are supposed to have arisen has been made clear in previous articles, but it will facilitate our present study to note that they took their starts from two main sources: (1) solar molecules driven into orbits by the original solar expulsion, and (2) molecules thrown out into orbits from the nuclei later by molecular interaction. There were other sources of planetesimals, but they may be neglected here. In both classes the planetesimals started as molecules chiefly. To some extent they may have been newly formed precipitates from the solar gases, or precipitate aggregates formed by the union of the fresh precipitates. Such precipitates are thought to form in the sun's photosphere now. They would be likely to have been formed by the expansion of the solar gases just after these emerged from solar pressure. The essential point here is that, whether molecules, precipitates, or precipitate aggregates, they were minute. Whether they afterward grew to notable sizes depended on the conditions that controlled their later history. Chief among the controlling influences were the dynamic properties given the planetesimals by their expulsion, and the gravitative stresses that controlled the field into which they were driven. It is to be kept ever in mind that they were bodies projected into swift independent flight, each

in its own path under control of its own inertia and the gravitative stresses of its environment. The planetesimals shot out from the nuclei had the simpler history, and are easiest followed to gain typical pictures of planetesimal behavior as a basis for estimates of their modes and rates of infall.

Let us picture the earth nucleus as pursuing a nearly circular orbit about the sun while certain of its outer molecules were escaping from it in various directions by reason of exceptional velocities given them by cumulative successions of rebounds from favorable collisions. It is easy to fall into the error of supposing that these molecules, thus escaping in different directions, would take orbits quite discordant with that of the nucleus and thus pass into the meteoritic rather than the planetesimal class. As constituents of the nucleus, they already had motions relative to the sun, and of course carried these with them they went into orbits of their own, except in so far as these motions were reduced or increased by their ejection from the nucleus. The velocity of the nucleus in its orbit should have been of the order of eighteen miles per second, and that of all the molecules of the nucleus about the same, some a little more, some a little less, by reason of their participation in rotation, et cet. It was the new and additional velocity which the escaping molecule had been given, *measured at the border of the sphere of control of the nucleus*, which determined its orbit after it had escaped. Only in extremely rare cases would molecular interaction give to an escaping molecule a speed greater than the parabolic velocity respecting the nucleus, that is a velocity sufficient to carry the molecule to infinity so far as the restraining attraction of the nucleus was concerned. The parabolic velocity of even the full-grown earth at the border of its sphere of control is 1.75 miles per second, so that we leave a large margin of safety if we assume that molecules almost never were shot away from the border of the sphere of control of the nucleus at more than two miles per second. Now, as the nucleus was moving at eighteen miles per second relative to the sun, a molecule shot directly backward would still have a velocity of sixteen miles per second relative to the sun, and a molecule shot directly forward would have a velocity of twenty miles per second relative to the sun, while

those shot out at lesser velocities, or sidewise at various angles, would have intermediate velocities. All would therefore be moving in the same general direction as the nucleus and their orbits would still be similar. The molecules in these new orbits would therefore be planetesimals, because they would revolve about the sun in orbits similar to those of the planets. The kinetic theory of gases requires us to suppose that molecules of the lighter gases escaped from the outer border of the earth-nucleus with some degree of frequency while it was hot and diffuse, and that such molecules have continued to escape from the outer border of the earth's atmosphere ever since, but much less frequently. And so of all other planets that have atmospheres, and of the sun as well. Practically all the molecules that thus escaped into orbits still remained within the sphere of control of the sun and were liable in time to be picked up again, so that this whole system of escape and recovery constitutes a mode of exchange of atmospheric material between the domains of the sun and the planets. It contributes to the maintenance and equilibrium of our atmosphere as elsewhere set forth.[1]

Let us now look to the gathering in of the planetesimals in this typical case, for that is the vital point here. Under the laws of mechanics the planetesimals shot forth in this way would come back to the virtual points of their escape at the end of each revolution in their new orbits, unless they were diverted by some intervening influence. From this it is easy to jump to the conclusion that they would all soon be picked up again by the nucleus, but not so, in general. They were nearly all thrown into larger or smaller orbits and that determined the *time* at which they should get back to the point of their origin. In most cases this was either earlier or later than the return of the nucleus and hence recapture was avoided. Figure 1 and the accompanying periodic data, prepared by Dr. MacMillan, make this very clear. From the point *A* at the top of the figure let one molecule be shot forward at a speed 10 per cent greater than that of the nucleus and let another molecule be shot backward so that its velocity shall be 10 per cent less than that of the nucleus. The first molecule will take the outer

[1] *The Origin of the Earth* (1916), pp. 13–17.

orbit, the second, the inner orbit. The molecule in the inner orbit will get back to *A* in .77 of the time required by the nucleus to reach this point, while the molecule in the outer orbit will require 1.424 times that period, i.e., if it takes the nucleus three hundred and sixty-five days to complete its orbit, the planestesimal that was shot backward and took the inner orbit would reach *A* eighty-four days ahead of the nucleus, while the molecule that was shot ahead and took the larger orbit would return to *A* one hundred

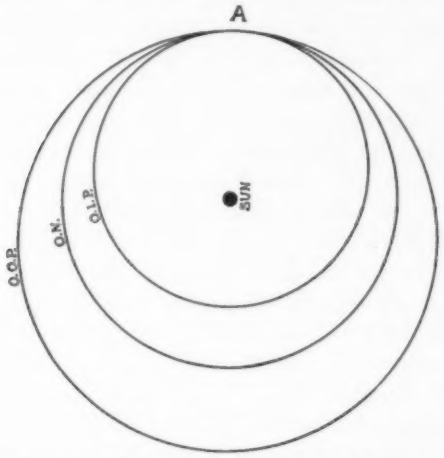

FIG. 1.—O.N. represents the orbit of the nucleus; O.O.P., the orbit of the outer planetesimal; O.I.P., the orbit of the inner planetesimal. Periodic times, earth = 1; inner planetesimal = 0.77; outer planetesimal = 1.424 (MacMillan).

and fifty-five days after the nucleus had passed. There was therefore no immediate danger of collision and recapture in either case. Only by waiting for a concurrence of the schedules, which would be liable to be thwarted by perturbations, or by a protracted series of orbital shiftings, or by changes of orbital form or dimensions, could this be brought about.

Were these planetesimal molecules likely to unite with one another in the course of their flights and so grow to larger sizes? The figure illustrates this point also. It is very obvious that the two planetesimals specified have no opportunity at all to unite

with one another until they return to the vicinity of A. But one of them would reach A two hundred and thirty-nine days earlier than the other. Even in this specially favorable case when they had a common node there was no immediate opportunity for union. Of course cases of less divergence could be chosen in which there was a nearer coincidence of orbits and of time schedules, and if there were many orbits there would be some real crossings farther from the nucleus, but those chosen illustrate the prevalent fact that even though such bodies have similar orbits and sometimes actual crossings, they may yet remain independent for long periods. Their mutual attractions would, in general, aid in bringing this about ultimately, but instead of this they might be brought into co-ordinate orbits like those of the earth and moon and revolve together in harmony indefinitely. At best the process was likely to be a very slow one. The picture of molecules drawn directly together, as in the case of static bodies or of gases, is very commonly substituted for the real case, and is very misleading. When all possible cases are considered, as well as the multitude of planetesimals, there are enough chances of collision and coalescence, especially with the nuclei, to make the process of ingathering effective in the course of long periods, but in its very nature it cannot be a speedy process. When planetesimal molecules or even precipitate aggregates collide, rebound would be more likely to follow than coalescence, unless they were electrically charged. Coalescence almost inevitably follows collision with nuclei but not encounters between planetesimals.

This simple example of the evolution and behavior of planetesimals illustrates the mechanism by which they are maintained and the contingencies of their capture or their mutual coalescence, where the conditions are exceptionally favorable. For the case most important in the formation of the earth, we must turn to the solar molecules which were driven directly into orbits by the original propulsion from the sun under the stimulus and attraction of the co-operating body. These were subject to the law of return to the points of their origin, but they were greatly diverted by the pull of the co-operating body and so largely lost all such systematic relations to a given nucleus as those that made the previous case

so simple and instructive. The orbits in this case were distributed through greater space and more irregularly, and hence their coalescence with one another and their capture by the planetary nuclei, as a rule, required greater changes in the forms, dimensions, and attitudes of their orbits. We will turn to concrete specifications and numerical values presently.

THE SIZE OF PLANETESIMALS NOT IMPORTANT IN RESPECT TO MELTING EFFECTS

Lest we stress the growth of planetesimals too much, it is prudent to observe at once that the sizes of the planetesimals were not matters of vital moment so far as the total energy-effect of their infall was concerned, for whatever was gained by concentration of mass was lost by less frequent infalls. On the whole, less energy available for conversion into heat was carried into the earth by the united planetesimals than by the same mass ununited, for in coming together, energy of motion was converted into heat and this was dissipated at the point of union in open space; the combined mass carried so much less energy into the earth-core. However, whenever combination took place, there was relatively less resistance and heating of the atmosphere in plunging through it, and so relatively more heating of the surface of the earth. As we shall see a little later, however, the chief effect at the earth's surface was lateral dispersion and an elastic or explosive reaction, resulting in a great scattering of débris with little obvious melting. None the less, we shall consider the melting effects of large planetesimals as well as small ones.

THE LIGHT SHED ON SIZE BY EXISTING PLANETESIMALS

It has been shown in previous papers[1] that the union of molecules and the growth of small aggregates could take place with more or less facility up to a certain order of size, but that beyond such order conditions unfavorable to further growth arose and increased relatively, so that indefinite growth was probably limited, as a general rule. It appeared that chemical, electrical, and

[1] Article X, this *Journal*, Vol. XXVIII, No. 2 (February–March, 1920), pp. 140–44.

cohesive attractions functioned effectively in the early stages; but that fragmentation, abrasion, and exfoliation came into increasing effectiveness as larger sizes were attained. Theoretically, then, growth from the minute state at which the planetesimals started, took place presumably up to limited sizes with relative facility, beyond which the presumption of much larger growth was adverse, except under unusual conditions. Theory, however, does not define at all closely where the balance between the opposing agencies was to be found, and so we turn to naturalistic evidence which is more decisive.

1. *The zodiacal planetesimals.*—It is an accepted view that the zodiacal light is due to the reflection of solar light from minute solid or liquid particles distributed in a lenslike form about the sun. The central plane of the lens is essentially coincident with the common plane of the planetary system. The outer border of the lens reaches to some undetermined distance beyond the earth. Under favorable conditions, it is possible to trace the counterglow (*Gegenschein*), on the side of the earth opposite the sun, into continuity with the zodiacal light on the sunward side. It is not improbable that the edge of the lens is extremely attenuated and extends indefinitely outward in the plane of the planets. The form and extent of the lens in the planetary plane make it scarcely less than certain that the particles are sustained by orbital dynamics, and that the orbits are of the planetary type and that hence the particles are planetesimals. This warrants us in turning to them for light on the sizes and masses of planetesimals. Their testimony is obvious for they are certainly quite small.

Though they envelop the earth and must in many cases be quite near, the individual planetesimals are too small for detection. Although they are certainly very numerous, their joint mass is not known to affect the motions of any body. They are interpreted either as remnants of the original planetesimal system, or as more recent products due to the projection of solar matter so close to the planets that it is drawn forward by them into elliptical orbits about the sun. If the first view is correct, or in so far as it is correct, the planetesimals are exceptionally old and should

have reached the fullest growth to which they are ordinarily subject. If they are of more recent origin, they merely bear testimony to the common size to which planetesimals of the younger order attain. But as they are so obviously minute their testimony in either case is weighty.

2. *The satellitesimals of Saturn's rings.*—Satellitesimals are merely special forms of planetesimals. It is convenient to distinguish between them in certain cases, while in other cases the generic term planestesimal is most satisfactory. In the Saturnian case, they are notable for their very close association with one another and for their definite borders. These hint at a special origin, perhaps the disintegration of a satellite by the differential attraction of Saturn, since they lie within its Roche limit. At any rate, the closeness of the individual satellitesimals to one another gives them rather pointed bearing on the question of growth to large sizes, for their nearness to one another should favor this, if mutual attraction has any appreciable effect. According to Bell's studies of their albedo, they are chiefly very minute particles.[1] Only rarely is there evidence of masses reaching as much as a meter in diameter. Trituration as a consequence of their mutual collisions is probably the dominant size-controlling agency in this case.

3. *Precipitate aggregates formed from condensing gases. The chondrules.*—When the gases or vapors of stony and metallic substances mixed with lighter gases were expelled from the sun into the vacuum of interplanetary space, they must probably have been greatly expanded and cooled and the stony and metallic substances thrown down as precipitates at successive stages according as the appropriate temperatures were reached. As each gaseous substance was diffused through the others, the precipitates could at first have been little more than molecular in size, but by subsequent interaction, in the fashion of Brownian particles, the first precipitates were brought into contact with one another and in their fresh, hot, viscous states should have united into larger aggregates rather freely. In so far as they solidified, they naturally

[1] Louis Bell, "The Physical Interpretation of Albedo, II, Saturn's Rings," *Astrophys. Jour.*, Vol. L (July, 1919), pp. 1–22.

took the form of concretions or of crystals. I have ventured to suggest that this may be the mode in which chondrules—little organized bodies that enter into the formation of 90 per cent of known meteorites—were formed. Later I shall suggest that the formation of the common small meteors of the sky may have taken place in practically the same way as planetesimals, i.e., by the progressive aggregation of precipitates from the stony and metallic ingredients of solar gases shot into interplanetary space and there cooled, the distinction between the two being their orbital characters and planetary relations. If these suggestions are in the line of truth, the chondrules give very specific evidence on the usual sizes of planetesimals, for they range from the size of a walnut down to fine dustlike particles.

4. *The negative evidence.*—Concurrent with these concrete sources of evidence, supported by theory, is the significant fact that no bodies of a distinctly larger or *planetoidal* order of magnitude are seen to revolve in the region of the earth's orbit or within it. We have found reasons for suspecting that the normal dynamic stresses in this inner solar region have always been too great to permit the collective aggregation of precipitate clouds of so little mass. At any rate, the negative testimony of observation stands against any view that postulates an abundance of bodies of planetoidal size in the region of the earth or their effective participation in the formative processes of the earth or the moon.

Let us then assume that the chondrules are our best naturalistic guide in respect to the normal sizes of planetesimals. For definiteness in the computations that follow, let us assume as a convenient representative weight, one-fiftieth of a pound, say one-third of an ounce, or about 9 grams. In testing the probability, or otherwise, that planetesimal infalls would produce a molten state of the growing earth-core, it will make no essential difference whether the planetesimals were somewhat larger or somewhat smaller than this size which is adopted merely for definiteness and convenience. After inspection of the melting effects in a case thus made as nearly normal as we conveniently can, we will try to test the effects of supposedly larger planetesimals.

THE TIME OVER WHICH THE INGATHERING OF PLANETESIMALS WAS SPREAD

It is obvious that the time over which the infall of planetesimals was spread is an essential factor in determining whether the heat of their infall would melt the earth surface or not. And so if there are any naturalistic evidences bearing on this point, they should be brought under consideration at once so that they may serve as guides or tests where assumptions have to be made in trying to deduce the period of infall from the mechanics of the case. Successful study of earth history has been found to rest much more largely on naturalistic considerations than on deduction, especially when the premises involve so much that is assumptive. An approach along naturalistic lines may be found in biologic evolution combined with geologic chronology.

1. *The intimations of biologic evolution.*—It seems to be the consensus of opinion among those best fitted to judge that the portion of life-evolution that has taken place since the faunas and floras of the early Paleozoic offered a fair criterion for judgment, is of the order of one-tenth of the total life-evolution, or some such proportion. This proportion will therefore be made the basis of the time-scale used in the following discussion. It will be easy to modify the results of the computations to suit any other proportion that may be thought nearer the reality. I do not think that any other proportion which is tenable will change the general tenor of the conclusions, so far as these bear on the melting effects of planetesimal infall.

Two geologic time-scales are now in use, an older one built on estimates of the present rates of geological progress, and a newer one built on radioactive processes. For myself I regard the latter as much the more trustworthy. The former seems to me to need radical correction (1) for the exceptional speed of present denudation due to the stripping of very large portions of the surface of its native protection, and (2) for the exceptional speed induced by the present high relief of the surface brought about by recent diastrophism.[1] But let us use both scales. Those who prefer

[1] See Article VIII of this series, "The Quantitative Element in Circumcontinental Growth," this *Journal*, Vol. XXII (1914), pp. 516–26.

the old scale will doubtless concede that the *proportions* of the radioactive scale may be used safely as a means of extending the older scale over the Proterozoic and Archean eras, where its own criteria are not available. Using the radioactive scale, the beginning of the Paleozoic may be placed, in round figures, at 4×10^8 years ago, the beginning of the Proterozoic at 12×10^8 years, and the oldest portion of the Archean that has been determined in respect to age, at 16×10^8 years. Using the old scale, the beginning of the Paleozoic may be placed at 10^8 years and—using the radioactive scale for proportionate extension—the beginning of the Proterozoic at 3×10^8 years, and the earliest determined Archean at 4×10^8 years. To fill out the *total* period of life-evolution on the radioactive scale, an allowance of 24×10^8 years *previous* to the earliest determined Archean must be made, making the total life-period 4×10^9 years. To similarly fill out the total period of life-evolution on the old scale, 6×10^8 years is to be allowed previous to the earliest determined Archean, and 10×10^8 years for the whole life-period.

In thus using the proportions of biologic evolution as an indication of the period over which the growing stage of the earth was spread, it is to be noticed that, to avoid making the assigned period of planetesimal infall unfairly long by including too much of the tailing-out stage, I shall consider all planetesimals that fell during the last 400,000,000 years (radioactive scale) of the Archean era, and all that have fallen since, 16×10^8 years in all, as though they had fallen within the computed period. On the other hand, all that fell during the nuclear stage, i.e., before a definite earth-core was formed, are necessarily excluded from the estimated period of life-evolution, since the conditions were incompatible with life. No doubt the infall during the distinctly nebulous portion of the nuclear stage may have been more rapid than during the biologic stage but that does not concern us in considering the period of biologic activity preceding the earliest age-determined Archean. It is the special merit of the planetesimal hypothesis that it takes due account of biological requirements, as generously interpreted as the leaders in biological inquiry demand. The biological

evidences are regarded as among the most cogent that bear upon the duration of the early history of the earth.

Qualified and defined as thus specified, the period of effective planetesimal infall subsequent to the nuclear stage is made to range from 600,000,000 years on the old geological scale, to 2,400,000,000 years on what seems to me to be the more probable radioactive scale.

These assignments of time may impress some readers as very long, but the question is to be asked anew, are they longer than the biological evidence requires? We shall soon inquire whether they are any longer than the mechanics of the case warrant. But before passing on, it is to be noted that the interpretation of biological evolution should no longer suffer from duress due to supposed limitations of time, such as were vigorously urged during the last half of the last century by advocates of the contractional theory of the sun's heat and of other physical tenets which were really less well grounded than the biological and geological interpretations. This alien stress is now not only lifted, but a new theoretical urgency of precisely opposite import has taken its place, a seemingly imperative need to find a source of heat for the maintenance of the stars of such potency as will enable them to serve their indicated functions in the protracted history of star clusters and our stellar galaxy. For this, a stellar longevity of the order of ten billion years, or some such great period, seems to be required. Short of trespassing on some such time allowance as that, biology and geology cannot be said to be necessarily restricted for lack of solar endurance. The seeming demand of biological and geological evidences for a total earth age of three or four billion years need not be thought extravagant or unreasonable, if either class of evidence is found to really require it.

2. *The intimations of the planetesimal mechanism.*—Let us now turn to the planetesimal mechanism to see what may be its most probable time requirements. Neglecting planetesimals of high and unusual orbital range, a fair and at the same time conservative working approximation to the extent of that portion of the planetesimal field which was tributary to the earth, may be made by

taking the width of the tract now occupied by the planetoids as its breadth, and for its depth the limits of the earth's dominant attraction in competition with that of Mars on the outside, and that of Venus on the inside. These give roundly 55×10^6 miles in breadth and 58×10^6 in depth. They define the cross-section of the planetesimal ring which curved around the sun with the path of the earth-core near its center. The actual field was much larger than this, but the planetesimals outside these limits are neglected to compensate for any lateral thinning inside. The area of the cross-section was therefore roundly 3×10^{15} square miles and its curved length 292×10^6 miles. For a working case of the medium order, let the mass of the earth-core, at the beginning of the specified period of planetesimal infall, be taken as one-third of the final earth-mass, leaving two-thirds of the earth-mass in the form of planetesimals to be gathered in. It will be seen that this proportion makes the mass of the planetesimals large and favors effective infall. It is taken merely as a fair working basis without any intention of implying an opinion as to the ratio of the nuclear to the planetesimal portions which actually obtained; that may best be reserved for further study. Taking the masses and dimensions of Mars and Venus as guides, in accordance with our comparative studies (Article X), the earth-core should have had a diameter of about 6,000 miles. Its disk would then have an area of 28×10^6 square miles, roundly. This is the fleeting target which the widely scattered planetesimals must hit, if they were to take part in the earth-building, or to change the simile, this is the area of the sweeper that must gather in the planetesimals from their vast field to build its one-third mass up to a three-thirds mass.

1. As rigorous treatment is impracticable, modes of approximation are our only recourse; and so, as a simple and purely artificial first approach, suited to give a realistic impression of the immensity of the field that must be swept, let us suppose that the planetesimals stand still while the earth-disk sweeps through it at its normal speed, changing its path in such an effective way as to clean up an entirely new swath at each revolution. Even by this impossibly speedy method, 100,000,000 years, roundly, would be required.

2. To make a first approach of a natural kind that can be treated mathematically, Dr. MacMillan has suggested that the planetesimals might be treated as though they were particles of gas which would close in upon the track of the earth-core as it revolved through the center of the tract, though the dynamics of gases are radically different from those of planetesimals, and corrections must be made accordingly. To gather in all the planetesimals under these conditions would take an indefinite period; to gather in 90 per cent would require somewhat over 260,000,000 years. Keeping in mind that this is not the real case, but merely one that can easily be treated, it is worth while to note that one-fifteenth of the earth-mass would fall in after 260,000,000 years had passed and that nine-fifteenths would be systematically distributed over this period with infall greatest at the start in due proportion, but it does not give warrant for excessive concentration in the early stages. If that is assumed, it makes the more certain a non-melting rate in the later stages and the infall during these would furnish the outer shell of the earth to a depth beyond the reach of most problems of immediate geologic interest. The vital point, however, is that in this substitute case, like the real one, the laws of mechanics require a distribution of infall over long periods.

3. The next step toward the real case is the substitution of heterogeneously revolving particles for the previous gaseous particles. A gaseous organization is a failing structure in the sense that when any inner portion of it is removed the rest collapses sufficiently to fill the space. In an orbital organization no such collapse takes place, each remaining body is sustained in its orbit by its own moving force. This makes a radical difference in the rate of ingathering by a body like the earth-core in the case in hand. Those planetesimals whose paths had actual crossings with that of the earth-core would be picked up, if not disturbed by perturbation, whenever their time schedules became coincident at the crossing, but not before, normally. Those planetesimals—by far the greater number—which had no such actual crossings at the start, would circle through their independent orbits indefinitely,

if they were not thrown out by collision, which would be rare in such vast space, or perturbed by other bodies, among which the earth-core would be the most influential in most cases. But such perturbations work very slowly, and their effects on the orbits involved are not easily visualized by any except experts in orbital dynamics. It is easy, however, to see that the case is far different from the direct collapse of gaseous particles and that it must occupy much greater time. In the lack of any rigorous determination of just how much longer the ingathering process would take, we may merely note that if it be taken as no more than two or three times longer, the total period would at least equal the biological requirements given above on the older geological scale.

But such bodies in heterogeneous orbits belong to the meteoritic type, and would not arise normally from the dynamic influences postulated by the planetesimal hypothesis, nor would their aggregation give rise to planets in concurrent revolution, for lack of the requisite moment of momentum, unless it were assigned them by some supplementary hypothesis such as revolution of the whole assemblage. As in the preceding case this assumption only serves as a step toward the real case.

4. The distinctive feature of the postulated planetesimals was that *they were moving in the same general direction as the collecting body and at the same general rate of speed*. The process of collection was therefore confined to overtakes and to convergencies of orbits. The differences between this and the preceding case may be compared to the different degrees of danger of collision between automobiles when, in one case, they are running in a common direction, on the right side of the road, under fairly well regulated speeds, and, in the other case, running wildly at random in both direction and speed. So planetesimals, circling about the sun in more or less concurrent orbits, only collide and coalesce in so far as they deviate from concurrence with the rest of the system or are perturbed in their independent orbits and drawn into coalescence by overtakes or convergencies. In so far as their orbits were concurrent, the moment of momentum of the combined mass was nearly as high as the sum of the individual moments of momenta, and so, if at any stage the orbits became adjusted to one another, they

might revolve in harmony indefinitely, as do the earth and moon. It was this concurrency of movement that made the evolution of a planetary system highly endowed with moment of momentum a possibility. Therein lies the soul of the planetesimal theory. But evolution under these conditions requires great lapses of time.

But lest this be overstressed, it is to be noted that the subparallelism of orbits and the subequality of speeds gave greater effect to the mutual attractions of the earth-core and the planetesimals, and so tended either to bring them together or else into harmoniously adjusted orbits, such as those of the earth and its satellite. Compared with the much more familiar gaseous and meteoritic types, the fundamental tendency of a planetesimal system is *not so much direct concentration as concurrent revolution*, though, in so far as the nuclei are competent, they gather in the smaller bodies. It seems clear, therefore, that the time required for collecting the planetesimals would be some multiple of that assigned in the preceding case. It is not clear just how large it would be, but if taken at three or four, the total time requirement would equal the maximum estimate of the biological requirement. In the nature of the case, it should not be less, for life-evolution could not proceed until a solid core was formed and the rate of infalling planetesimals permitted a congenial temperature. At any rate, however large may be the latitude for different numerical estimates of the total time and rate of planetesimal infall, it is altogether clear that a precipitate ingathering is incompatible with the mechanics of the planetesimal system.

THE RATES OF PLANETESIMAL INFALL

a) *The infall of normal planetesimals.*—We have already found reasons for thinking that the planetesimals were usually small, as their name implies, and have chosen one-fiftieth of a pound as a working figure. We have also chosen one-third of the total mass of the earth as the amount of material already in the earth-core and two-thirds as the amount still in the form of planetesimals at the beginning of the specified period of infall.

The mass of the present earth is 6×10^{21} tons. There would then be 4×10^{26} planetesimals of the specified mass to be gathered

into the core to complete the growth of the earth. The earth-core, taken at 6,000 miles in diameter, would have a surface area of 3×10^{15} square feet. As there were 4×10^{26} planetesimals in all, 13×10^{10} planetesimals must fall upon each foot of earth-core surface, on the average, to build the body up to its present mass.

Now, if we take the total period of infall, as given above on the radio-geo-biologic scale, at 2.4×10^{9} years, a planetesimal one-fiftieth of a pound in weight, falling upon each square foot every 6.7 days, or a little less than once a week, would have completed the growth of the earth in the time specified. It will be agreed, I think, that this does not remotely approach a rate sufficient to melt the earth surface. If there is any doubt as to the dissipation of energy following the impact of a falling body, see later discussions.

If we take as the period of infall the biological requirements as estimated on the older geologic time-scale, 6×10^{8} years, a planetesimal falling upon a square foot once in about forty hours would build the earth up to its present mass in the time estimated. This again, I think it will be agreed, is not near the melting-rate for the general surface.

If we make the time of infall equal to the highest of our range of estimates from the mechanics of the case, 3×10^{9} years, an average fall of a planetesimal on each square foot once in a little over eight days would suffice, or if we take the minimum of the estimates, 18×10^{8}, a planetesimal once in about five days would answer, in either case far from a general melting-rate.

If we fall back upon the untenable assumption that the planetesimals distributed themselves after the manner of gaseous particles—made merely as a first step in approach—and take the computed 26×10^{7} years as the total time, the average rate of infall upon each square foot would be about one planetesimal in seventeen hours. Even this does not seem to be a rate that would threaten the melting of the earth, and yet it is much more rapid than is permitted by the mechanics of the real case under the basal assumptions made.

Let us now reverse the mode of inquiry by trying to approximate a rate of infall that would cause the melting of the earth surface, and then compare results with those reached in the preceding ways.

If the mass of the earth-core equaled one-third that of the present earth, an atmosphere of sufficient depth to protect its surface from the direct impact of planetesimals of the specified mass would have surrounded it. The melting of the earth must then have hung upon the competency of the infall to so heat the upper atmosphere as to melt the earth surface some miles below. About half the heat acquired by the thin upper air would have been quite promptly radiated outward and the melting left to the other half. The effect of the air on meteorites plunging into it is suggestive in this connection. As soon as a film of meteorite-substance becomes viscous enough to yield to the high pressure of the air condensed on the meteorite's front by its high speed, the film is driven backward and dissipated along the meteor's path forming the "streak" of the "shooting star." Only a very small part is melted at any one instant, or left in any one spot. Even this minute part only reaches the first stages of the molten state and hence is very quickly cooled again to the solid state. To apply this to planetesimals, it is to be noted that the mean velocity of meteorities is probably four or five times that of normal planetesimals, and their moving energies sixteen to twenty-five times as great in proportion to mass. The working picture, then, in the case in hand, is that of a little mass, one-fiftieth of a pound, making a similar but feebler streak of quickly heated, quickly cooled matter, down the center of a column of air one square foot in cross-section. This must take place in such close succession as to melt one square foot of the earth surface at the bottom of the atmosphere in spite of outward radiation. To really complete the picture, it is necessary to add that the lower atmosphere would soon be filled with the dust of the dissipated planetesimals and the melting of the surface would have to be effected through this screen. It seems clear that to effect general melting the upper atmosphere must be heated throughout to the melting-point of average rock-substance, and kept at that temperature in spite of

convection and radiation. As radiation increases with the fourth power of the temperature, it would be very effective as the red-hot stage was approached.

As the case is beyond the reach of experiment or rigorous computation, specific estimates of rate can be little more than matters of judgment. Let us therefore resort to the serial method, which sometimes leads to a decisive conclusion even when definite quantitative values are unavailable.[1] Let each reader fix upon such rate of infall as seems to him competent to produce a molten state of the earth surface under the given conditions. Let us then see how such a rate fits into the range of rates which the mechanics of the case permits. Too great a discrepancy may be about as decisive as if the precise rates were known. The working test is the final arbiter.

If one's assumption is that a planetesimal plunged into the upper end of each square-foot air-column once every second, the column would be built up to the present surface in 4,119 years. It will be recalled that our first, but wholly arbitrary and exceptionally speedy mode of sweeping up the planetesimal field required 100,000,000 years and the most speedy natural method 260,000,000. and that both of these hypothetical cases required less time than the real case.

If one planetesimal fell upon each square foot once per minute, the total time would still be only 247,140 years. The competency of such a rate to melt the earth surface would, I think, at least be open to question.

If the rate were one planetesimal per hour, the total period would be 14,828,400 years, which is about one-seventeenth of the time of ingathering required on even the gaseous assumption. Moreover this rate would give a cooling period to every column of air more than 3,000 times as long as the glowing period, estimated from the mean duration of "shooting stars."

At one planetesimal per day per square foot, the total time would be 355,881,600 years. I think it will be agreed that this rate of infall would fall far below a liquefying rate, and yet even

[1] "The Methods of the Earth Sciences," *Pop. Sci. Mo.* (November, 1904), pp. 70 and 71 ("The Method of Multiple Series").

so fast a rate of infall as this does not seem to be warranted by the mechanics of the case.

Apparently the only line of escape from the import of such a serial trial lies in postulating that the rate of infall in the earliest stages was sufficiently more rapid than the mean rate to effect melting in such early period. A declining rate of infall is, of course, to be presumed, and has been taken into account. The rate used in the computations is the mean rate for the specified accession when assumed to be distributed over only the period which *followed* the formation of the earth-core and *preceded* the earliest time-determined Archean, 16×10^8 years ago. The accessions before that period were reckoned as part of the mass of the earth-core, and the accessions since were thrown into the specified period to avoid counting the long tailing-out period of 1,600,000,000 years (radioactive scale). The period thus made the basis of computation represents an intermediate stage of infall and was given the benefit constructively of all subsequent infall. We excluded such infall as was contemporaneous with the evolution of the nucleus from its nebulous state until a definite earth-core was formed, because it necessarily preceded life-evolution, and because it is not separable from nebulous condensation and the other nuclear conditions. In connection with the irregularities of the original outburst, there may have arisen some incalculable rates of infall. These would doubtless have made themselves felt chiefly in the nuclear stages. Our endeavor was to include in the computations only the systematic ingathering into which the action settled as a secular process. The physical state of the nucleus during its evolution from a nebulous state into an earth-core has been left an open question, reserved for further consideration. Meanwhile, a molten state during that period has been treated as one of the alternatives, and as a not improbable one. The infall of planetesimals during that stage may probably have been an important factor in determining the state which actually prevailed. But all that is held to antedate the growth of the outer part of the earth. This embraces about all that has yet been brought under study in geological and biological inquiries. To reach a satisfactory basis for these inquiries is the soul of the present issue. The state of

the core does not radically affect most geological and petrological problems.

The infall of supposedly large planetesimals.—In the foregoing tests it has been assumed that planetesimals normally grew to about the same order of size as the chondrules, and that the disruptions and abrasions they suffered after reaching this size kept them down to about the order of the little masses that form "shooting stars." Let us now consider the melting effects likely to follow if the planetesimals had grown to very much larger sizes. To keep as close to the actual as practicable, let us base our first study on the phenomena of Coon Butte, or Meteor Crater, Arizona, interpreted as the work of a gigantic meteorite, or cluster of meteorites or, if you please, the nucleus of a comet, accepting as conclusive, in the main, the disclosures of the drillings, shafts, and trenches of Barringer and Tilghman. Then, let us base our second study on the craters of the moon, on the assumption—made solely for the sake of the study and without acceptance—that they were formed by the impacts of still larger bodies.

Case I. The testimony of Coon Butte or Meteor Crater.—There is no reason to think that the celestial mass whose plunge into the earth formed Coon Butte was a planetesimal, because, among other reasons, it came from the northward, an unlikely direction for a planetesimal and because its indicated velocity was probably too high. The work done by it, however, is very instructive respecting the physical effects of such a falling mass under natural conditions.

The essential phenomena are a circular rim of upturned strata, covered thickly by outthrown débris, 130 to 160 feet above the surrounding plain, inclosing a crater nearly 4,000 feet in diameter and 440 feet deep, measured from the original surface of the horizontal sandstone and limestone from which the crater was formed to the top of the present partial filling.[1] Crushed rock, mingled

[1] The following are among the more important papers on the subject: A. E. Fotte, *Amer. Jour. of Sci.*, Vol. XLII (1891), p. 413; also *Proc. Amer. Assoc. Adv. Sci.*, Vol. XL (1892), pp. 279–83; G. K. Gilbert, *13th Ann. Rept., U.S. Geol. Surv.*, Part I (1892), p. 98; *14th Ann. Rept.*, Part I, (1893), p. 187; *Geol. Soc. of Wash.* (President's Address), March, 1896; *Science* (N.S.), Vol. III (1896), pp. 1–13; O. A. Derby, "Constituents of the Canyon Diablo Meteorite," *Amer. Jour. of Sci.*, Vol. XLIX

with meteoritic matter, lies below the floor of the crater to a depth of about 660 feet. Below this, disrupted rock seems to grade into undisturbed sandstone at points between 1,100 and 1,200 feet beneath the general plain. Rock masses and clastic material, coarse and fine, were thrown from the pit and strewn over the adjacent plain for distances of one to two miles on all sides, while meteoritic matter, distributed subconcentrically, reaches out to an extreme distance of $5\frac{1}{2}$ miles. The rim and pit, while subsymmetrical, have sufficient asymmetry to indicate an infall from a northerly direction, perhaps N. NW. to S. SE. The chief mechanical effects were the formation of the crater by the breaking up of perhaps 8×10^8 tons of rock, and the hurling out of perhaps half of it, the turning up to high angles of the previously horizontal limestone and sandstone beds of the crater-border, the crushing of large quantities of sandstone to silicious rock flour, and the development of some schistosity in connection with it. The chief thermal effects were the partial metamorphism of some of the rock flour and the development of incipient fusion in other portions of it, some of this portion becoming vesicular. The crushing and heating were obviously the direct effects of the impact, the upturning of the rim and projection of the débris as obviously the effects of the attending lateral thrust and the quasi-explosive reaction that followed.

The energy involved in the mechanical effects must be subtracted from the total energy of the impact before the heating effects can be theoretically deduced. The very large sum total of these mechanical effects shows how great would be the error of computing the energy of infall in terms of heat and using that as

(Feb., 1895), pp. 101–10; D. M. Barringer and B. C. Tilghman, "First Mention of the Discovery that the Crater Is an Impact Crater and Not a Crater Produced by a Steam Explosion" (President's Statement), *Proc. of Acad. Nat. Sci.* (Philadelphia, Dec. 5, 1905); D. M. Barringer, "Coon Mountain and Its Crater," *Proc. Acad. Nat. Sci.* (Philadelphia, Dec., 1905), pp. 861–86 (issued March 1, 1906); B. C. Tilghman, "Coon Butte, Arizona," *ibid.*, pp. 887–914; J. W. Mallet, *Amer. Jour. of Sci.*, Vol. XXI (May, 1906), pp. 347–55; J. C. Branner, *Science*, Vol. XXIV (Sept. 21, 1906), pp. 370–71; H. L. Fairchild, at Tenth Session of the International Geological Congress, in Mexico, September 14, 1906, *Compte Rendu, X Session, Congrès Géol. Inter.* (Mexico, 1906), p. 147; O. C. Farrington, "Analysis of Siderite Oxides or Iron Shale," *Amer. Jour. of Sci.*, Vol. XXII (Oct., 1906), pp. 303–9.

a measure of the melting effects. This would be a tempting line of attack but is quite inadmissible because the mechanical effects alone call for more energy than can be reasonably assigned to the meteoritic material found. The only safe recourse is the direct evidence. The heating effects implied by the direct evidence are singularly small compared with the mechanical effects. To a considerable, but not closely determined, extent, the crushed sandstone shows incipient schistosity with partial metamorphism, obviously a compressive effect, the heat of which did not rise to the grade of fusion. To a considerably smaller extent, if I interpret the descriptions correctly, the crushed sandstone shows the early stages of fusion, while some of this portion has become inflated and pumaceous, but no appreciable masses were left in the state of glass or other completely fused product. If fully melted matter was formed at all, it was probably dispersed by the explosive reaction. It seems quite clear that the portion which became vesicular did not become fully fused and fluent, for, in part at least, the bedding lines were not wholly obliterated. These portions seem, however, to have been rendered distinctly viscous and susceptible of inflation. This must probably have taken place during the resilience which followed the compression. The internal gases could scarcely have puffed the viscous rock while the intense pressure of the impact was on. If, on the other hand, they had remained viscous until the pressure from the falling back of the exploded débris was brought to bear, they would have collapsed, at least in all deeply buried portions. Apparently they had cooled in their inflated state while the pressure was off. It seems, therefore, that there was practically no liquid rock left when the explosive reaction was over. This is a matter of radical importance in its bearings on the question of producing a holo-liquid earth by such impacts. It shows that a very high proportion of the energy of impact was converted into another mechanical form, not into heat. There is no question about the greatness of the energy of impact; the mechanical work involved in the formation of the crater and of its rim, as also in the crushing and scattering of the débris, demonstrate that. And yet there is no evidence that this violent impact left even the smallest pool of lava. *The significant feature of the*

case lies in its clear evidence that the energy of impact was chiefly transformed into lateral thrust and resilience of quasi-explosive type. Confessedly the most outstanding problem left is to find a source of energy adequate to the mechanical effects so impressively forced on attention. The case still remains something of a puzzle on that account. Meteoric matter has been found so widely disseminated through the débris, both within and without the crater, that the origin of the crater is no longer in doubt, but yet the amount of meteoric matter thus far brought into evidence seems clearly too small to be adequate. The suggestion of Barringer that the infalling mass was a cluster of meteorites or a comet's head is plausible in itself—and the orbits of comets are such as to make a bump into the earth a recognized contingency—but these suggestions give little help in the matter of adequacy. A larger mass than has been found seems to be required to satisfy the effects realized. For such computations as I have made, a siderite sphere 400 to 500 feet in diameter was taken, but it is scarcely worth while to give the results here. They are of the same import as those of the next case.

We ought not to overlook the fact that this is the only known case of such an infall in the history of the earth. This is an embarrassment in postulating a rapid series of infalls. Nor is its negative bearing merely a surface matter. If such a crater had been formed and buried in a natural way in any geologic formation, however old, there would be a fair chance of its detection. There is therefore a complete absence of geological warrant for supposing that infalls of this kind were ever anything but very sporadic affairs. If Meteor Crater was formed by the impact of the nucleus of a comet, theory would make its repetition an extremely rare event. The concept of an enormous meteorite, or close cluster of meteorites, other than cometic, has no observational basis. If the views respecting the origin of meteorites, later expressed in this article, have any cogency, the infall of such bodies would be governed by the same order of chances as those of comets. From no point of view, therefore, does Meteor Crater offer substantial ground for supposing that the earth was once molten because of the impacts of meteoritic bodies.

Case II. The questionable intimations of the craters of the moon.— The impact theory of the craters of the moon affords a concrete basis for the study of infalls of a still larger order. To fit this case, bodies of the order of five miles in diameter, more or less, seem to be required, and for working convenience these may be given the specific gravity of the moon, 3.34. The assumed size in this case has about the same ratio to the larger order of the moon's craters that the assumed 400 or 500 foot meteoritic body had to the size of Meteor Crater, but the mass is made relatively less to be in better accord with the moon's mass. The size is about the lower limit assigned to planetoids. No atmosphere can be supposed to have broken the effects of infall in this case or to have checked the free dispersal of the débris.

In the previous case there was surprisingly little evidence of liquefaction. What is the evidence here? The steep walls of the deep craters are quite incompatible with a liquid state, so far as this outermost part is concerned and this is the part subject to direct impact. There was strength enough in the crust to support the lunar Alps and Apennines, some of whose peaks tower to heights of 20,000 feet and more above the adjacent surface, i.e., 5,000 feet higher than their terrestrial prototypes. No less than ten mountain ranges have been recognized on the moon, which implies general crustal strength. The great relief of such elevations towering above such depressions is uncontrovertible evidence of strength and stability. The significance of this is emphasized, if the supposed impacts are made a part of the formative process of the moon, for then they are very old and have stood in this strong relief in spite of all the creep of the geologic ages.

A search for direct evidences of molten matter gives meager results under the most favorable interpretation that is tenable. Such of the craters as have level bottoms have been thought to imply a partial filling of lava, supposed to have risen from below after the craters had been formed. These bottoms may, however, be interpreted as level beds of clastic débris, like those that form the level bottom of Meteor Crater. So, also, the seemingly smooth, but really quite accidented, plains of the "maria" have been interpreted as great lava flows, but these may likewise be merely débris

plains. In the best photographs they are seen to have considerable relief and to be crisscrossed in different directions by lines of débris obviously shot from neighboring craters. They are thus at least surficially covered with clastic débris. But granting that everything which appears at this distance like lava really is lava, the whole does not imply a liquefaction of the moon of any other order than that signified by the great lava flows on the earth whose essential solidity is now beyond question.

But let us look at the question of rapid infall quantitatively and numerically. Let us assume that at the beginning of the accretion process, one-third of the mass of the moon was already in its core, while the remaining two-thirds had been gathered into bolides five miles in diameter which were yet to fall in. The mass of the moon is about 732×10^{17} tons. There would then have been 244×10^{17} tons in the moon-core and 488×10^{17} tons in the bolides yet to fall in. The mass of each of these bolides would have been about 997×10^{9} tons, and their total number about 49×10^{6}. Their individual volumes would have been a little over sixty-five cubic miles, while the volume of the moon-core would have been about 14×10^{8} cubic miles, and the radius of the core 708 miles. As the radius of the full-grown moon is 1,080 miles, the core would have had to grow radially 372 miles.

Now the surface area of the moon-core would have been 6×10^{6} square miles, while the disk of the five-mile bolides was a trifle less than twenty square miles in area, so that there would have been over 300,000 disk-areas on the surface of the moon-core. It would thus have required less than two hundred bolides to each disk-area to complete the full growth of the moon.

The liquid-forming impact theory now takes a critical form. We have seen that the surface of the moon shows that the last craters were not attended by general liquefaction or even a viscous state of their immediate walls. The last falls, however, were accelerated by nearly the full mass of the present moon, while the first falls were accelerated by only one-third the mass of the moon. The individual effects of the last infalls should, therefore, have been greater than any that preceded. They should also have inherited whatever benefits were transmissible from previous

infalls, in proportion to the time between falls. As these last impacts left no conclusive evidence of molten residue, it follows that no previous infall, in itself, can be consistently supposed to have left any greater molten residue and if their inheritance was greater it could apparently only come from a closer succession of infalls. Apparently, then, the only way in which a general molten condition can reasonably be supposed to have arisen was from the cumulative effects of such inherited residues of heat from the earlier infalls in excess of those of the later infalls. How tenable is this? There were by computation less than two hundred infalls of the specified kind to each disk-area during the whole accretion period of the moon. If that accretion period were essentially the same as that of the earth, as it should theoretically be, and if we compute the rate of infall by using the minimum accretion period assigned the earth based on mechanical and biological evidences, to make the rate as high as consistent, the mean interval between impacts would be about 3,000,000 years. If the mean accretion period had been used, the mean interval between infalls would have been more than twice this time. Very little inheritance of heat from a surficial bump can be postulated over an interval of this order.

But we are not left wholly to computations on estimated requirements. There is the direct evidence of the craters themselves. Some are fresh and their débris lines lie straight across older pits and older features of all sorts. Some pits and rims are worn or buried to the very limit of recognition, and there are all grades between. These features offer no warrant for the hypothesis that there was a closely crowded infall. They distinctly imply that the formation of the visible craters stretched over a long period. This evidence is the more cogent when the limited means of denudation, owing to the absence of an atmosphere and hydrosphere on the moon, are considered.

Now let us turn to the theory itself. If it be supposed that the five-mile bolides are planetesimals, the supposition itself hides under its cloak a quasi-assertion of the rate of their infall, for, as we have seen, all planetesimals started as very minute bodies controlled by a system of dynamics that imposed upon them slow growth as a

necessity of the limited amount of planetesimal matter, the large amount of space through which it was distributed, and the mutual relations of the planetesimal orbits, as already brought out. There were besides obstacles to growth beyond quite small sizes. Even if these obstacles be supposed to have been ineffectual, time for growth from the minute sizes to five-mile bolides must have intervened before the latter could function as crater-formers. They could thus have come into function only at a late stage. But accretion could not have been suspended in the meantime. They could therefore have come into function only as a *partial* source of lunar accretion. Growth from the smaller planetesimals must have gone forward during all the intervening period. Accretion simply by such giant planetesimals is thus incompatible with the fundamental conditions postulated by the basal hypothesis on which it rests.

The hypothesis is not much more promising if planetoids are substituted for the supposed giant planetesimals, for, by the mechanics of the case, the planetoids were given courses less favorable to aggregation than were the planetesimals, and hence greater intervals between their infalls must in consistency be assumed. This is in harmony with the observed fact that at least eight hundred planetoids are still following their own individual paths in a relatively limited tract and yet no collision or even dangerous approach to one another has been noted during the whole period of astronomical observation. In addition to this, we have found reasons for doubting whether planetoids could organize as nuclei of the planetary type under the differential stresses of the solar attractions that prevail in the region of the earth and in regions still nearer the sun.

The hypothesis that the pits of the moon were formed by the impacts of great meteorites offers no presumption that one infall would be followed by another in the same spot within any short period. As a cause of general melting, this is even more unpromising than the preceding.

The discussion thus far has proceeded on the assumption that the pits of the moon are the scars left by the impacts of great bolides of one sort or another. Before turning to the next topic,

it may be well to forestall misapprehension by making clear our view that such an origin of the craters of the moon is in itself improbable, for bodies moving in orbits under the control of the sun should plunge into the moon, if they strike it at all, at various angles to the vertical. In many cases the stroke should be quite oblique to the surface and should leave elongated pits, unsymmetrical rims, unequal dispersions of débris, and other tell-tale features; all the more so because the moon had no atmosphere to retard and turn downward the path of the bolides. Apparently the only escape from these grave objections lies in supposing that the explosive reaction was so great that it completely overwhelmed the effects of the direct stroke. If this assumption were tenable, it would seem to imply that the explosive dispersion was so great that it must have scattered all mobile matter, and especially all liquid matter so effectually as to insure its cooling while in flight.

THE SIGNIFICANCE OF THE EXPLOSIVE PHENOMENA OF THE MOON

The moon seems to have been a paradise of Krakatoas and Katmais. Interpreted as the product of gaseous explosion, the abundance and the greatness of the craters of the moon carry special significance. They have commonly been thought to imply a once molten state of the moon. I think the argument lies in precisely the opposite direction. If the moon, in its formative stage had been a molten globe, its high temperature should have set free all gases susceptible of being freed by any temperature that ever arose afterward. Its liquid state and its convective circulation would have brought these gases to the surface and given them opportunities of escape never equaled later, for the high temperature of the surface would have forced unsurpassed molecular activity and have insured their escape from the control of the moon. Even the cold full-grown moon cannot hold the volcanic gases. After all such gases had been boiled out of the moon and had escaped, and the gas-free lava had cooled, the moon should have been devoid of the means of explosive action.

On the other hand, if the moon were built up of minute clastic particles which carried such amounts of occluded and combined gases as meteorites do, and as they naturally would from their

long flights in the ultra-atmospheric field of the sun, and if the porous surface of the moon received and held by adsorption, chemical combination, or otherwise, molecular planetesimals of the gas-forming order, such as would inevitably plunge into it from the interplanetary field, there would be entrapped in the body of the moon, as it grew, a supply of disseminated gas-producing material sufficient to actuate great explosions whenever concentrated later by conditions favorable for such action. As the moon grew, its self-compression and the strains developed within it by neighboring bodies should have forced this potentially gaseous material toward the surface and developed the conditions of eruption. The moon should also have inherited its quota of radioactive substances and these should have played their part in the lunar vulcanicity. The fragmental constitution of the outer part of the moon, postulated as an inevitable feature of an accretional origin, should have rendered it specially susceptible to explosive effects. More or less local lava-production, as well as the quiet type of vulcanism, are entirely consistent with this view of the exceptionally gaseous eruptions, and they are postulated, but the evidence of the moon's surface seems to give this more quiet action a place quite subordinate to the gaseo-explosive phase.

THE SIGNIFICANCE OF TERRESTRIAL VULCANISM

The inferences that seem so imperative in the case of the moon apply also to the gaseous phases of vulcanism on the earth. The argument is a little less imperative because the earth is able to hold an atmosphere and would probably do so to some less extent in a molten state, and so, if it were once in that state, volcanic gases could have been retained in its liquid mass sufficient to balance the partial pressures of the like gases in such lessened atmosphere as the earth then held. The amount of gases so held in equilibrium could not have been large, and such as existed would not have served as explosive agencies because of the very fact that they were held in balance by opposing pressure. They were there merely because there was an outside pressure holding them there and that outside pressure was never removed under normal conditions. It seems merely declaiming the obvious to say that

such a gas content is incompetent to produce explosive eruptions and that such eruptions occur on the earth only when there are special developments or accumulations of gas within or beneath the exploded matter. In a molten earth, stirred during its long cooling stages by effective convection,[1] the gases set free by the various stages of heat of that period should have been so far brought to the surface and dissipated by molecular activity—except the limited equilibrium amount—that the earth when cooled and solidified should have been as deficient in explosive material as lavas are now found by experiment to be when melted in the open air at the surface and, after a long stage of boiling, cooled to the solid state. In essence, therefore, the case of the earth is the same as that of the moon. The studies of terrestrial volcanoes of recent years have brought forth accumulating evidence that volcanoes are actuated by inborn rather than outside gases, and that they are essentially independent of one another, though of course not independent of common conditions. Their explosiveness seems thus clearly due to their own individual resources and has no obvious dependence on any molten zone, sheet, pool, or other remnant of a once pervasive liquid state.

THE TESTIMONY OF THE ABERRANT BODIES OF THE SOLAR SYSTEM

We have now considered at some length the bearings of various lines of evidence drawn from the normal elements of the solar system. Let us turn for a moment to such suggestions as may be derived from the aberrant members of the system, the meteors, meteorites, and comets. If these are merely aliens that have been introduced incidentally from foreign sources, as some of them may be, there is little reason to expect them to teach much relative to the domestic organization; but if they were born in the system and are products of its dynamics, they may be quite as instructive as the normal members.

To discuss them with any definiteness, however, it is necessary to postulate the modes by which they came into being. These should reveal why they are aberrant, though products of the same

[1] See pp. 481–87 of previous article, this *Journal*, Vol. XXVIII (1920).

dynamics as the normal elements. I venture, therefore, to offer three hypothetical, but mutually consistent, ways in which meteors, meteorites, and comets may have arisen naturally and inevitably out of the dynamical system that gave rise to the planets as its normal product.

The problem of the meteors, meteorites, and comets is regarded as essentially one. Though complete demonstration has perhaps not yet been reached, it is assumed that meteors, meteorites, and comets are not only close of kin dynamically, but in some sense mutual derivatives. The spectacular phenomena which seem to put comets in a class by themselves are here supposed to be mainly the effects of the strongly contrasted conditions to which they are subjected at the extremes of their very elongated orbits. It is a suggestive fact that those comets which are supposed to have been reduced from extremely elongated orbits to shorter ones by the action of the great planets, show a notable tendency to lose their spectacular features and finally to pass by disintegration into meteor swarms. In the case of typical comets of extremely elongated orbits, a small loosely organized head—apparently a cluster of still smaller bodies held together by rather feeble gravitative control—swings from a relatively hot perihelion close to the sun to a very cold aphelion far out in space. During its long outer journey, all the constituents must become intensely cold to great depths and be liable to be deeply riven by shrinkage cracks, which, besides leading to coarse fragmentation, should facilitate the adsorption of molecules belonging to the sun's ultra-atmosphere. The action is supposed to be the same as that which gives to meteorites their occluded or combined gases. The outward swing of the comet occupies many years and often centuries, and there is time for even a very attenuated source of supply to furnish the requisite amount of gas-producing material.

When later the comet head, thus charged, approaches the sun, the gases are supposed to be set free by the solar heat on the sunward side, and to be driven forth toward the sun. At the same time, this differential heating is supposed to give rise to rapid and rather violent exfoliation, hurling the dissevered chips to

considerable distances against the feeble gravity of the head. By collisions in the course of their flights, these develop a quasi-gaseous meteoritic swarm whose triturative action should give rise to products of dustlike fineness. Both of these processes would doubtless be attended by much electrical dissociation in which the negative electrons would escape and the positive remain attached, so that electric repulsion would tend to drive both gases and dust sunward until repellant action from the sun reversed the movement and drove the whole backward in the form of the comet's tail. This sketch is very inadequate, but it may serve to suggest ways in which the distinctive features of comets may arise. The nuclei of the comets' heads may be merely clouds or clustered groups of meteorite-like masses loosely assembled by their own feeble attractions, and so subject to easy deployment and reassemblage as conditions require.

If the spectacular features of comets may thus be reduced to the incidental effects of extremely elongated orbits, the way is cleared for explaining how the material of the meteors, meteorites, and comet-heads may have originated, how their highly elliptical orbits were given them, and why these orbits lie in all azimuths and the bodies in them revolve indifferently in forward and retrograde directions in contrast to the systematic, orderly, and concurrent habits of the planetary bodies.

1. The first hypothesis assumes that, previous to the genesis of the present planetary system, the sun had a system of secondaries of the type which it could generate *without the co-operation of any outside body*. The assigned principles of such generation are those rigorous deductions from the kinetic theory of gases on which orbital ultra-atmospheres are postulated.[1] This class of secondaries would be, in the nature of the case, of a very much smaller order than our present planets. The orbits of such bodies would be likely to be thrown into erratic courses by the near approach of the massive body to which the origin of our present planetary system is assigned. Such of these small bodies as were thrown into very long elliptical orbits were made to suffer great extremes of heat and cold and might thus, it is postulated, have taken on

[1] "Celestial Kinships," *The Origin of the Earth* (1916), pp. 101–2.

cometic features, for a time, and later suffered dispersion into meteors and meteorites.

If any of these ancestral secondaries had attained a notable size and happened to be disturbed so as to be drawn through the Roche limit of the sun, it might be disrupted and become a clustered group suited to serve as the nucleus of a comet. This, however, would not be likely to occur in many cases, and so appeal is made chiefly to the riving action of cold in the aphelion journey as the dependable cause for the disrupted character of the comets' heads, and the fragmental features which meteorites commonly show.

2. The second hypothesis assumes that forces of the kinds disclosed by the observations of Pettit on the solar prominences of May 29 and July 15, 1919,[1] projected solar gases and precipitates into the outer regions of the sun's sphere of control, where its attraction was feeble, and where the attractions of neighboring stars and star groups were relatively strong. During these outer flights, the pull of some star, group of stars, or other outside source of attraction drew the ejected masses aside from their normal paths sufficiently to cause them to swing by the sun on their return and thus be forced to take highly elliptical orbits. The planes of these orbits and the direction of revolution thus generated would be determined by the various deviating attractions, so that a system formed by a large number of such deviations would be very heterogeneous orbitally. High ellipticity would be a common characteristic. The principles that control aggregation, as previously sketched in this series of papers, would apply to the projected matter in all such cases. In so far as this matter retained self-control, it would assemble by the precipitate-aggregate method into clouds of aggregates, and these would usually be still more closely assembled into loosely organized bodies well suited to function as the nuclei of comet-heads. These would be subject to all the vicissitudes of temperature and of alternate absorption and evolution of gaseous material, sketched above, and so display for a time the spectacular features of comets, and ultimately be disintegrated into meteorites. In so far as the projected solar matter was too highly dispersed for mutual control, it should have passed

[1] *Astrophys. Jour.* (Oct., 1919), pp. 206–19.

directly into meteoritic matter of the minutest type. At present, meteoritic particles, assumed to be of this type, abound in interplanetary space in such prodigious numbers that many millions are picked up daily by the earth. The formation of precipitate aggregates, in the methods previously sketched, seems to furnish an apt explanation of the origin of chondrules and of the other minute integers that so largely make up meteorites. The collisions of these little bodies as they were entering into the formation of larger bodies, seem well fitted to account for the intimate brecciation, the minute specks of glass, suddenly cooled liquid drops, as well as the strange mixtures of stony and metallic matter, and other distinctive features of meteorites.

3. The third hypothesis is dependent on the pre-existence of the present planetary system. It supposes that the ejected solar matter passed so near some one of the more massive planets that it was thrown into an elliptical orbit in a way similar to the preceding and with similar results. A certain portion of the particles so diverted would take orbits of the planetary type, so far as their planes are concerned, but only a part of these would have a planetoidal degree of circularity. Other portions would have orbits whose eccentricities, orbital planes, and directions of revolution were as various as are those of meteorites and comets. Certain comets are known to have orbits definitely related to the giant planets. This relation is commonly interpreted as the result of reduction from larger and more eccentric orbits by the planet's influence. Without questioning the validity of this interpretation, it is not inconsistent to hold that in a part of such cases, the comets arose *de novo* from planetary action in the way here suggested. Most comets developed in this way would probably belong to the feebly developed evanescent type.

These three hypotheses are entirely consistent with one another and may all be true. They have the merit of being made to rest on the same dynamic basis as the planetary system itself. These hypotheses for the aberrant factors, when added to the planetesimal hypothesis for the normal factors, give a theoretical unity to the whole solar system.

Now, if these are the true lines of interpretation, *the masses of meteors and meteorites, and their methods of infall, throw a flood of light on the sizes and the modes of infall of the planetesimals, for, by this interpretation, they are bodies of like origin and like general conditions.* On a conservative estimate, there are 100,000,000 or more minute meteorites, so small as to be wholly dissipated in the upper air, for every one that is massive enough to remain a visible body until it reaches the earth. Of the latter, none are known to exceed a dozen feet in mean diameter. No meteorite has ever been seen to produce melted soil or rock by its impact. When collisions with bodies that have no atmosphere take place, local melting probably results. The glassy bodies common in meteorites may very likely be such products. But the retention of such heterogeneous structures as are common in meteorites implies that there has been no *general* liquefaction. In so far, therefore, as the testimony of the aberrant factors bears on the size, rate of infall, and liquefying power of their dynamic relatives, the planetesimals, it supports the view that these are small, and in other respects it is in close accord with the deductions hereinbefore drawn from dynamical considerations. It is in intimate harmony with the testimony of the normal factors of the system.

Professor F. R. Moulton and Dr. W. D. MacMillan have been kind enough to read the manuscript of this and the three previous articles (X, XI, and XII), and to make valuable suggestions and criticisms. They are not responsible, however, for the computations. These have been verified by Miss Daisy W. Heath.

A PLEISTOCENE PENEPLAIN IN THE COASTAL PLAIN

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The Black Belt of Alabama is famous throughout the state, and in the surrounding states, for its great fertility, its production of cotton and corn, the levelness of its plantations, the large proportion of negroes to whites, and its numerous ante-bellum mansions—the visible manifestations of its former wealth.

As one rides over the gently undulating surface of the region, with its deep black soil, and crosses the steep-sided gullies and the bluff-bordered rivers, he is impressed with the aspect of topographic youth. However, a more careful study in the field and of the geological literature forces one to the conclusion that the region is not in the youthful stage of a first cycle of erosion, nor in a mature stage of erosion, but that the surface is a recently raised plain, so flat as almost to make the term peneplain—almost a plain—inappropriate. The following excellent description will assist one in visualizing the region:

> The surface of the country, underlaid by the Rotten Limestone, is but little diversified; it is, however, occasionally broken into rounded bald knolls, as may be seen between Arcola and Demopolis, and between Livingston and Sumterville. The summits of these hillocks are sometimes ornamented with cedars, but more frequently they are quite bare, or covered with but a scanty vegetation; even where the surface is but slightly undulating, bald spots occur where the naked rock has come up. But the most remarkable feature of this region is the extensive tracts of land covered with a deep, black soil of great depth and extraordinary fertility, which may be seen in various parts of Sumter, Greene, Marengo, Perry, and Dallas, but more particularly in the "cane brake." The surface of these remarkable tracts has barely sufficient inclination to admit of easy drainage, without giving the water force enough to remove the soil, so that, instead of excavating a channel at the bottom of the trough-like depressions where this sort of land occurs, it is absorbed by the soil, or spreads over a considerable space, where it loses all transporting power.

> The unbroken surface of this region is due to the homogeneous character of the limestone, which suffers waste equally on this account, over considerable areas; and hence the entire absence of ravines, and other abrupt irregularities. . . . . In the uncleared parts of the cane brake, ... one can scarcely satisfy himself that he is not standing on the low grounds of a river; the deep, alluvial-looking soil beneath his feet, the moisture-loving long moss (Tillandsia usneoides) above his head, together with an undergrowth of Sabals, Palmettoes, and other natives of damp soils, strengthen the illusion.[1]

Professor Eugene A. Smith's accurate and suggestive description is as follows:

> The Selma chalk underlies a belt entering the State from Mississippi and extending eastward with an average width of 20 to 25 miles, to a short distance beyond Montgomery, where its distinctive characters are lost or merged into those of the "blue-marl region." . . . . The somewhat uniform composition of the Selma chalk has caused it to be more deeply and evenly wasted by erosion and solution than the more sandy formations north and south of it. As a consequence, its outcrop is in the shape of a trough, with a gently undulating, almost unbroken surface except where remnants of the once continuous Lafayette mantle have protected the underlying limestone from erosion and have thus formed knobs and ridges capped with its loams and pebbles.
>
> In this belt, more than in any other of the Coastal Plain, the soils show their residuary character. They are, as a rule, highly calcareous clays and, where much mixed with organic matters, of black color. Throughout this section are areas originally destitute of trees and hence known as "prairies." From the agricultural point of view, the Selma chalk or black belt is the most highly favored part of the State and, apart from the cities, holds the densest population.[2]

R. M. Harper[3] characterizes the topography as "gently undulating in a manner difficult to describe, though probably due almost wholly to normal erosion processes," and points out that "some of the region, mostly remote from the rivers, is so level that the railroads have built straight tangents (i.e., straight tracks) a dozen or more miles in length." He also points out the rarity of swamps. The region is traversed by rivers that are, in most places, bordered by steep, bare bluffs—in some places 60 feet

[1] *Tuomey's Second Biennial Report*, pp. 134–37, 1848, quoted by Eugene A. Smith in his report on the *Geology of the Coastal Plain of Alabama* (1894), pp. 282–84.

[2] *Underground Water Resources of Alabama* (1907), p. 13.

[3] Roland M. Harper, "Economic Botany of Alabama," *Geographical Report on Forests*, Monograph 8, Part 1, 1913.

high—of chalky limestone, and the tributary streams have all the characteristics of youth.

The sides of the Black Belt trough are bounded on the north and south by ridges, formed of the more resistant strata of the Coastal Plain, which rise 200 to 300 feet above the general level of the surface. The pronounced cuesta which forms the southern border of the trough is composed of the sandy, more resistant Ripley (Cretaceous) sediments.

The Black Belt, Black Prairie, Cotton Belt, or Cane Brake, as it has been variously called, can be briefly described as a belt of rich, black soil with an average width of 20 to 25 miles, and an area in Alabama of about 4,300 square miles. It extends in an east-west direction in south central Alabama and conforms exactly with an easily decomposed, impure, chalky limestone of rather uniform composition (Selma chalk) which has a thickness of about 1,000 feet in the western part of the state and thins out and disappears in the east near Montgomery. This formation dips to the south at the rate of 30 to 40 feet to the mile while the surface slopes at a much less rapid rate in the same direction. It is the weathering of the beveled edges of this limestone that determines the width and position of the Black Belt. The soil formed from this rock is a clay of exceptional fertility but somewhat difficult to cultivate because it bakes in summer and becomes tenacious mud in winter.

After the deposition of the Coastal Plain sediments a deposit of red sandy loam, called the Lafayette formation, was laid down on them, either during the early Pleistocene or near the close of the Pliocene, and formed a veritable mantle covering many hundreds of square miles. The depth of this formation is, in places, as much as fifty feet, but little of it has a thickness of more than 25 feet. The origin of the Lafayette has given rise to much discussion,[1] but as the underlying formations in Alabama contain little quartz from which pebbles could be made, the abundant waterworn quartz pebbles show that in this state, at least, it must have been transported long distances. On the sides of the Black Belt trough some knobs and ridges are capped by this deposit, proving

[1] W. W. Shaw, *U.S. Prof. Paper 108 H.*

that the Black Belt was once covered with it. The almost complete absence of the Lafayette over the area underlain by the Selma chalk and its presence on other parts of the Coastal Plain north and south is attributable to the greater ease with which the chalk is weathered and eroded. Because of its solubility and lack of strength, the streams that flow through the limestone quickly cut their beds to grade. In other parts of the Coastal Plain which are underlain by limestone, it is also found that very little remains of the once widespread cover of Lafayette.

The features which lead to the belief that the Black Belt of Alabama is in the youthful stage of a first cycle of erosion was based upon the facts (1) that its surface is so level in certain areas as to give it an appearance of topographic youth; (2) that the rivers are bordered by steep banks or bluffs and are in a youthful stage of an erosion cycle.

The evidences which indicate that the region was peneplained and has been elevated in comparatively recent times are: (1) that it occupies a troughlike depression 200 to 300 feet lower than the bordering lands to the north and south; (2) that, although the soil is a clay, and is consequently very favorable for the retention of water, swamps are nevertheless uncommon except in river bottoms, showing that the drainage had been thoroughly established; (3) that the Lafayette, which once covered the Black Belt, has been almost entirely removed from it; (4) that the thick, residual soils of the region were probably formed chiefly after the land was reduced to a peneplain (at the present time they are being rapidly eroded away); (5) that the present youthful appearance of the region is due to a comparatively recent elevation of the peneplain 60 or more feet, which permitted the rivers to sink their beds; (6) that the peneplanation must have taken place during the Pleistocene, as is shown by the fact that the region was reduced to a nearly level surface and that a thick residual soil was formed after the removal of the Lafayette, a formation that was deposited not earlier than late Pliocene and, more probably, during the Pleistocene.

Estimates of the length of geological time are so uncertain that little dependence can be placed on them, but it is, nevertheless,

interesting to speculate upon the time required for the removal of the Lafayette loams, sands, and gravels from the Black Belt and for the reduction of the surface during part of the Pleistocene. Penck's estimate of 500,000 to 1,000,000 years for the duration of the Pleistocene, based upon the rate of advance and retreat of the Pleistocene Ice Sheets, is to be contrasted with Barrell's[1] minimum estimate of 1,500,000 years based upon a study of radioactivity. A few years ago Barrell's estimate would have seemed extravagant, but when one considers that a region, such as the one under discussion, has been denuded of a thick deposit of gravel and loam, has been reduced to a peneplain, has been weathered so long as to form a thick residual soil, has been raised, and, finally, has been so dissected by streams as to make a topography of youthful aspect, the larger estimate does not seem impossible.

In 1906, Chamberlin and Salisbury[2] presented figures as to the duration of time since the Kansan glacial epoch, giving 300,000 as a likely minimum, and 1,020,000 as a likely maximum. Had the statement covered the time since the beginning of the Pleistocene, these figures would have been considerably larger.

The physiographic history of the Coastal Plain of the Gulf of Mexico has not as yet been carefully worked out, and it is probable that a thorough study will show that this surface instead of being the youthful topography of a first cycle of erosion, is, for the most part, the incised surface of a peneplain or a plain of marine abrasion, in which are subordinate peneplains such as that of the Black Belt. The unconsolidated sediments and broad intervales give the impression of youth but the beveled edges of the formations which underlie the Coastal Plain and the level, outstanding cuesta ridges are suggestive of peneplanation. The writer hopes to be able to make a further study of the physiographic history of our Gulf Coastal Plain and with it a study of the Atlantic Coastal Plain.

[1] J. Barrell, "Measurements of Geological Time," *Geological Society of America Bulletin*, Vol. XXVIII (1917), p. 892.

[2] *Earth History*, Vol. III, p. 420.

THE MECHANICAL INTERPRETATION OF JOINTS[1]

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PART I

OUTLINE

The Joints on Mine Fork
Hartmann's Law
Hartmann's Law Applied to Experimental and Field Observations
- Compressive stress vertical, tensile stress horizontal
  - Experimental observations
  - The joints on Mine Fork, Magoffin County, Kentucky.
- Both, compressive and tensile stresses horizontal
  - Daubrée's experiments on Torsion
  - The joints on Crooked Creek, Adams County, Ohio
  - The joints of Lake Cayuga, New York
  - The joints of the Wisconsin shore of Lake Superior
  - The areal study of joint systems
- Greatest compression horizontal, least compression vertical
  - Small "symmetrical faults" of Lake Cayuga, New York
  - Experimental observations

I. THE JOINTS OF MINE FORK

In the course of field work in eastern Kentucky, in 1917, the writer observed a case of local jointing which gave him the clue to the following investigation.

On Mine Fork, a few hundred yards above the mouth of Lacy Creek, in Magoffin County, close to the Morgan and Johnson county lines, in a nearly vertical cliff of a strongly cross-bedded, coarse-grained sandstone forming the top of the Lee Group of the Pottsville series, the system of intersecting joints shown in the accompanying sketch (Fig. 1) is exposed along the roadside. Unfortunately the commercial work in which the writer was engaged at that time did not permit him to spend any more time in that vicinity than was necessary for a hasty survey of this exposure.

[1] Part I of this paper was presented, in essence, at the last meeting of Section "E" of the American Association for Advancement of Science, at St. Louis, December, 1919.

It was found that (*a*) The jointing is confined to the upper third (or even less) of the massive sandstone which is here about 100 feet thick. It is entirely lacking below. (*b*) It marks the crest of a minor anticline on the downthrow side of a conspicuous fault. (*c*) The average hade of the joint-traces on the practically vertical exposure which trends about in a NNE–SSW direction, is: set I: 27°—NNE; set II: 35°—SSW; inclosed angle: 62°. (*d*) The average strike of the joint-traces, measured on the horizontal surface of projecting ledges, is: set I: N 78 W; set II: N 27 W; inclosed angle: 51°. (*e*) The joints of set I are much better developed,

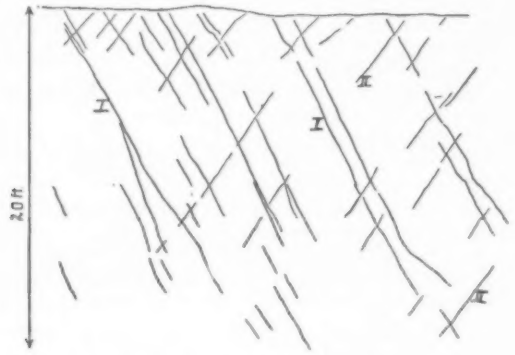

FIG. 1.—Jointing in vertical cliff of massive, cross-bedded sandstone on Mine Fork, Magoffin County, Kentucky.

longer, more continuous and more regular in their course than those of set II, both in the vertical and in the horizontal planes.

For two reasons the occurrence of this system of joints at this locality seemed surprising. There could be little doubt that these joints represented planes of shearing. The writer had, however, always associated the fracturing of hard materials by shearing with compressive stresses or, at best, with compound stresses resulting in torsion. But here he was dealing with a clear case of simple tension along the crest of an anticline, causing a hard sandstone to fail along typical planes of shearing.

He had also been accustomed to ascribe to the planes of maximum shear a general tendency to intersect at right angles. No

such tendency could be inferred from these joints, which intersect uniformly at an angle close to 60°, with the obtuse angle facing in the direction of the tensile stress.

II. HARTMANN'S LAW

Following the clue given by these observations, the author became acquainted with a book published in 1896 in Paris by L. Hartmann under the title *Distribution des déformations dans les métaux soumis á des efforts*,[1] containing a wealth of experimental data and a fascinating discussion of the lines forming on the surfaces of metals when strained beyond the elastic limit, known as Lüders' lines.[2]

When a highly polished plate of metal is subjected to a very gradually increasing simple tensile stress, the first permanent deformation is accompanied by the sudden appearance of one or several delicate straight lines or bands cutting in an oblique direction across its surface. Suitable illumination shows them to be depressions. When the stress is further increased, the existing lines widen and new ones appear, forming two conjugate systems of oblique lines, symmetrical to the direction of maximum stress and intersecting at a constant angle which in most metals (and rocks) is greater than 90°.[3] This angle remains unchanged with growing tension and is thus independent of the intensity of the stress. The final rupturing may entirely or partly follow these lines or cut across them at right angles to the tension.

Under compression, similar systems of lines form, but now the angle of intersection bisected by the direction of the compressive stress, for most rocks and metals, is smaller than 90°, and for the same material is the supplement of the one obtained under tension.

[1] Berger-Levrault, Paris, 1896.

[2] Called after Lüders of Magdeburg who first described them fully in 1860. "Über die Äusserung der Elastizität an stahlartigen Eisenstäben und über eine beim Biegen solcher Stäbe beobachtete Molekularbewegung," *Dingler's Polytech. Jour.*, Vol. CLV (1860), p. 18 (not seen).

[3] Ten good illustrations of strips of low steel showing yield lines developed under tensile stress, are given in H. Marten's *Handbook of Testing Materials* (translated by Gus. C. Henning), John Wiley & Sons, N.Y., 1899, Vol. I, Pl. 1, Figs. 3, 5, 12, 14–20.

The lines in this case are depressions only on one side, with the corresponding lines on the reverse side forming delicate ridges. Final rupturing, under compression, always follows these lines.

The great importance of these lines of Lüders for our purposes lies in the fact that they represent the outcrops of internal planes of yielding, differing largely in scale and degree of deformation, not in origin, from the planes of shearing observed on a large scale in nature.

In fact, in the small test piece as on a gigantic scale in nature, we see that the stress acts not uniformly on every unit of the mass undergoing deformation, but that it reaches a maximum along these geometrically distributed surfaces, while maintaining lower values in the volume between. We seem to be dealing here with a sharply defined application of the principle of least work.[1] At every point along every imaginary line of stress within a body undergoing elastic deformation there exists the tendency to shear in any one of an infinite number of directions all inclined to the direction of stress at the same angle, the sum of which forms two infinitely small cones joined by their apices.[2] Out of the infinite number of surfaces which may be obtained by connecting any two of such adjoining possible directions of shearing, those only will form which involve the expenditure of a minimum of energy.

When the lines of stress are not parallel, owing to the unequal distribution of stresses, the resulting surfaces of yielding may be very complex and the pattern of lines formed by their traces on the surface may be far from regular (Fig. 2*A*–*C*[3]).

In such cases Lüders' lines can be used to reconstruct the lines of maximum stress on any given test piece, by drawing the lines bisecting the angle of shear at every point of intersection of the shearing planes. Figure 2*C* represents the lines of stress derived in that way from Lüders' lines as obtained in the experiment illustrated in Figure 2*A* and *B*.

[1] H. von Helmholtz, "Über die physikalische Bedeutung des Princips der kleinsten Wirkung," *Wissenschaftliche Abhandlungen*, Vol. III, pp. 209–10.

[2] L. Hartmann, *op. cit.*, pp. 18–19.

[3] Hartman, *loc. cit.*, Figs. 48–50.

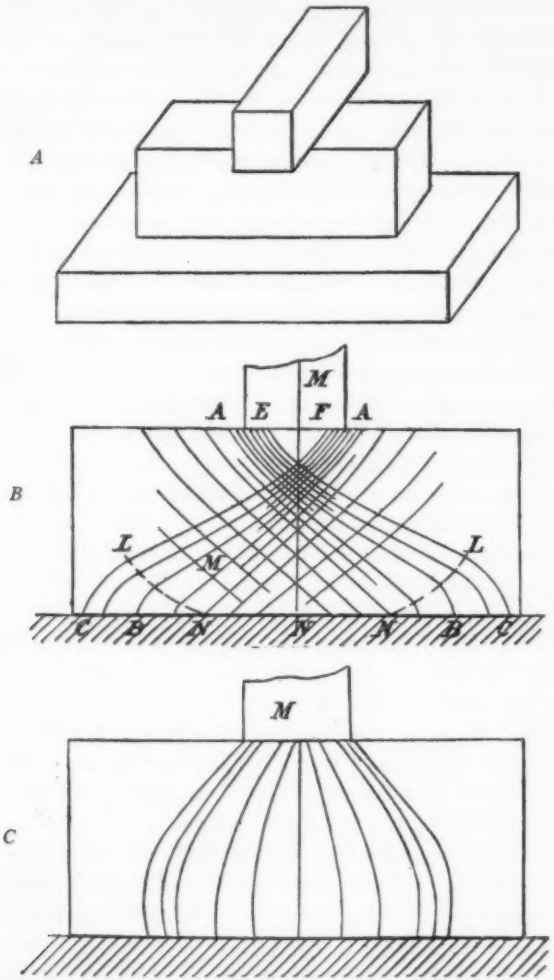

FIG. 2.—*A*. Arrangement used in one of Hartmann's experiments in which the test piece (in the center) was subjected to uniform compression over its whole base, while the upper surface suffered compression in the center only. (L. Hartmann, 1896.) *B*. Lüders' lines produced in the experiment illustrated in Fig. 2*A*. (L. Hartmann, 1896.) *C*. The theoretical lines of stress (bisecting the angles of Lüders' lines) reconstructed on the test piece illustrated in Fig. 2*B*. (L. Hartmann, 1896.)

The most irregular pattern of Lüders' lines results when the lines of stress are not parallel to the axis of the test piece, but intersect with it at varying angles. In that case, the angle formed by planes of yielding may be cut by the surface in all possible directions and the apparent angle of intersection of Lüders' lines as seen on the surface varies from point to point and must not be mistaken for the true constant angle bisected by the line of maximum stress of which it is only the oblique outcrop.

In 1900, O. Mohr published a mathematical study which led him to views practically identical with those of Hartmann. They may be summarized as follows:[1]

a) In all hard materials (except the most brittle ones), under tensional as well as compressional stresses, deformation by shearing takes place in two systems of intersecting planes of shearing.

b) Adjoining planes of one system are parallel.

c) The angle at which the two systems intersect is constant for any given material, that is, it is independent of the nature or intensity of the stresses involved.

d) For the same kind of material, this angle differs the more from 90° the harder and the more brittle the material is (e.g., hard or soft steel).

e) If we consider tension as negative compression, the law governing the arrangement of the yield planes with reference to the principal axes of stress which will be referred to as *Hartmann's Law*, can be expressed as follows: In brittle materials, *the acute angle formed by the shearing planes is bisected by the axis of maximum compression*, and *the obtuse angle by the axis of minimum compression which is generally negative, representing tension.*

f) If the position of the principal axes changes from point to point, the shearing surfaces are warped. The less this is the case, i.e., the more nearly homogeneous a material is, the more regular are the shearing planes.

g) The shearing planes do not originate simultaneously, and are not uniformly distributed.

[1] F. Rinne, "Vergleichende Untersuchungen über die Methoden zur Bestimmung der Druckfestigkeit von Gesteinen," *N. Jahrb. f. Min.*, etc., Vol. I (1907), p. 45.

III. HARTMANN'S LAW APPLIED TO EXPERIMENTAL AND FIELD OBSERVATIONS

Hartmann's law enables the geologist as well as the mechanical engineer to reconstruct the position of the principal axes of stress in any given body subject to mechanical deformation—be it a test specimen in the laboratory or the exposed portion of a fractured rock-mass—by analyzing from point to point the position of the planes of shearing. The direction bisecting the acute angle formed by the planes of shearing corresponds to that of the greatest principal axis of compressive stress, while the bisectrix of the obtuse angle gives the direction of the least stress, which in most cases represents active tensile stress. The direction of the intermediate principal stress coincides with the line of intersection of the two planes of shearing.

It is essential, however, to realize at the start the limitations of this law.

a) It applies only to brittle substances.

b) Not all lines of fracture are lines of shearing. Brittle materials, such as cast iron or hard steel, and most rocks under simple tension habitually fail along planes of fracture at right angles to the direction of maximum tensile stress.[1] Soft steel, on the other hand, fails along inclined planes of shearing under tension as well as under compression.

c) The position of the planes must be studied in space, not in any accidental plane of exposure.

d) The principal stresses inferred from them need not be identical with any real stresses, but may be only the resultants of the combined action of several stresses ("equivalent" stresses).

We may now proceed to test the usefulness of Hartmann's law by applying it to a few selected experimental data and geological field observations.

1. *Compressive stress vertical, tensile stress horizontal.*—*a*) When a cylindrical test piece is subjected to compression beyond the elastic limit, Lüders' lines make their appearance on its surface, forming a characteristic pattern of symmetrical intersecting spiral

[1] See, for instance, A. L. Jenkins, "Combined Stresses," *Jour. Amer. Soc. Mech. Engineers* (1917), p. 696.

lines, with the acute angles formed by their intersection facing the direction of pressure. On specimens of Carrara marble used by Rinne[1] this angle measured 60°, on those used by Kármán[2] it measured 54°, while red sandstone (*Buntsandstein*) gave a value as low as 38°.

When the pressure is increased until rupture occurs, the plane of fracture forms a symmetrical cone with an apical angle equaling the angle of shear characteristic of the material. In this case, the least principal stress equals the intermediate stress. Thereby its position is made indefinite with reference to the infinite number of directions in the plane common to the two lesser stresses, normal to the greatest principal stress. The peculiar conical fracture is the result.[3]

As soon, however, as any one of the infinite number of possible directions in the plane normal to the greatest stress offers a minimum of resistance, rupture occurs[4] along two well-defined planes, as indicated in Figure 3. Daubrée's classical experiments on blocks made of a mixture of plaster of Paris and beeswax[5] correspond directly to this case.

[1] F. Rinne, "Vergleichende Untersuchungen über die Methoden zur Bestimmung der Druckfestigkeit von Gesteinen," *Neues Jahrb. f. Miner.*, etc., Vol. I (1907), p. 45.

[2] Th. von Kármán, "Festigkeitsversuche unter allseitigem Druck," *Zeitschr. d. Vereins deutscher Ingenieure*, Vol. LV (1911), pp. 1748–57.

[3] The remarkable fracturing in the form of parallel and interpenetrating cones observed in the brittle white limestones of the Upper Jurassic along the intensely shattered margin of the crypto-volcanic basin of Steinheim seems to be due to this condition. W. Branco u. E. Fraas, "Das kryptovulkanische Becken von Steinheim," *Phys. Abhandl. d. K. Preuss. Akad. d. Wissensch.* (Berlin, 1905), pp. 36–38.

[4] In a cube where four directions offer an identical minimum of resistance, the planes of fracture form a pyramid as may be seen in any ordinary crushing test.

[5] A. Daubrée, "Études synthétiques de géologie expérimentale" (Paris, 1879), pp. 315 ff. and Figs. 93 and 94. For a copy of Fig. 93 see, e.g., Van Hise, "Principles of North American Pre-Cambrian Geology," *Sixteenth Ann. Rep. U.S.G.S.* (1895), Pt. I, p. 644, Fig. 126. Note in this figure the difference between Lüders' lines and the final plane of shearing. The former, marked "R," do not, at first, correspond to continuous internal surfaces. They represent purely local effects along individual lines of stress. The establishment of large planes of shearing (marked "F") is a later development. The difference between the two is shown strikingly on the right side of the block, where the main fracture cuts diagonally across Lüders' lines. This contrast between Lüders' lines and the final planes of rupture is met with in all experiments. It seems to indicate that at first the greatest tension exists parallel to the surface of the test specimen, due to the stretching of the horizontal dimensions accompanying the vertical shortening. Rupture, on the other hand, gives dominance to the direction of easiest movement in a radial direction.

b) It is easy to see that the joints on Mine Fork, Kentucky, described in the introduction to this paper, correspond to this type. Here, however, the active stress was the horizontal tension existing at the top of the anticline, while the weight of the overlying rock-masses, giving the compressive stress, was merely passive.

The analysis of joints can, however, be carried farther and may often yield information of decisive value to the field geologist.

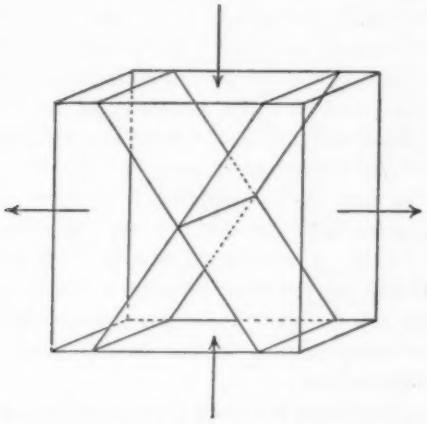

FIG. 3.—Diagram illustrating the position of the planes of shearing in a brittle body subjected simultaneously to vertical compression and horitonzal tension.

A detailed analysis of the joints on Mine Fork will be given here to illustrate the method of analysis used by the writer.

The exposure on Mine Fork is such as not to give the true dip of either of the joint planes. The joints themselves are filled with mineral matter and their surface is nowhere exposed. But their apparent hade was measured on the vertical face of the exposure trending essentially NNE—SSW and their strike was determined on the level top of the cliff.

	Set I	Set II
Apparent hade:	27° northward	35° southward
Strike:	N 78 W	N 27 W

A complete analysis from these data involves the following steps. Find

1. The actual position of the two planes in space.

2. The direction, in space, of the line of intersection of the two planes which corresponds to the position of the intermediate principal stress.

3. The position of the plane normal to this line.

4. The location in this plane of the other two principal stresses bisecting the acute and obtuse angles respectively.

The stereographic projection is admirably adapted to the demands of problems of this kind. By its use, the position of the principal stresses in space can be obtained in the field from any given set of joints within a few minutes. In the following brief description of the construction of Figure 4, a working knowledge of the stereographic projection is assumed.[1]

1. Draw the line *Ex-Ex*, trending N 23 E, to represent the vertical plane of the exposure. On it, mark the point *c*, 27° southward from *O*, and *c'*, 35° northward from *O*. The planes *acb* and *a'c'b'* represent the two joint planes and can now be drawn.

2. Since the two points *O* and *d* are common to both planes, *Od* is the line of intersection of the two planes, that is, the direction of the intermediate stress.

3. On the great circle *acb* mark point *e*, and similarly point *e'* on *a'c'b'*, both 90° from *d*. Through *e* and *e'* draw the great circle *fee'g*, representing the plane normal to *Od*. On it we can read directly the true value of the acute angle of the shearing planes, which in this case is 72°.

[1] For a detailed discussion of the stereographic projection see A. Johannsen, *Manual of Petrographic Methods*, p. 17. McGraw-Hill Book Co., 1914. For most purposes a protractor giving great circles and vertical small circles 10° apart, such as is given (after Penfield) in A. F. Rogers, *Introduction to the Study of Minerals* (McGraw-Hill Book Co., N.Y., 1912, pp. 82–86), is perfectly sufficient. It can readily be copied and carried in the notebook for use in the field. Greater accuracy can, of course, be obtained by the use of Wulff's net, a large copy of which is contained in E. E. Wright, "The Methods of Petrographic-Microscopic Research," *Carnegie Inst. Pub. 158*, Pl. III.

The reader who has had little practice in the use of the stereographic projection will find it easy to visualize Fig. 4 by remembering that the great circles must be imagined to be drawn on the surface of a hemisphere resting on the circle NESW with *O* at its center. A line such as *dO*, therefore, represents a radius extending from the surface of the hemisphere, at *d*, downward to the center *O*.

4. Find the point *i*, located halfway between *e* and *e'*. The line *iO*, lying in a plane normal to the intermediate stress *dO*, and in the plane *hidj* bisecting the acute angle of the shearing

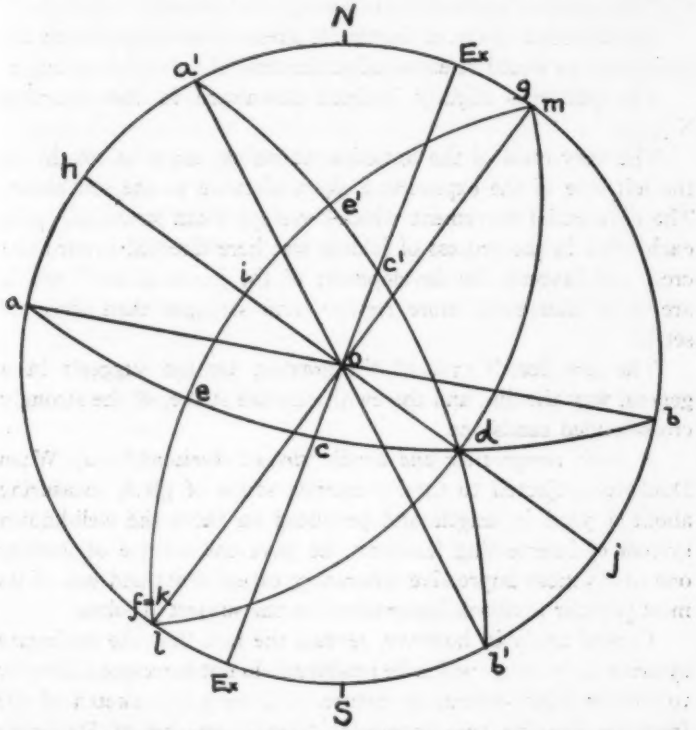

FIG. 4.—Stereographic projection of the joints on Mine Fork, Kentucky. *Ex*= Trend of exposure; *ab*=set I of joints; *a'b'*=set II of joints; *od*=line of intersection of joint planes=position of intermediate principal stress; *hidj*=plane bisecting the acute angle of the joint planes; *oi*=located in this plane, normal to *od*=position of the greatest (compressive) principal stress; *mdl*=plane bisecting the obtuse angle of the joint *hid* planes; *og*=located in the plane *mdl*, normal to *od*=least (tensile) principal stress; *mdl*, *gif*=principal planes.

planes, represents the direction in space of the compressive stress. The line *hj* gives the trend of this stress in a horizontal plane.

5. 90° from *i*, on the great circle *gif*, mark the point *k*, which in this case practically coincides with *f*. The line *kO*, lying in

the plane normal to *Od* and 90° from *Oi*, represents the direction in space of the tensile stress, and the line *ml*, in the vertical plane *lkdm*, gives the horizontal trend of this stress.

This analysis leads to the following conclusions:

The direction of *Ok*, of the tensile stress, differs only 3° from the horizontal, as would be expected at the crest of an anticlinal bulge.

The pull was slightly inclined downward in the direction N 33 E.

The very crest of the anticline, therefore, must be sought on the left side of the exposure, a short distance to the southwest. The differential movement which develops when strata slip past each other in the process of folding was here directed toward the crest and favored the development of the joints of set I which are more numerous, more regular, and stronger than those of set II.

The direction N 33 E of the greatest tension suggests in a general way the dip. and therewith also the strike, of the strongly cross-bedded sandstone.

2. *Both, compressive and tensile stresses horizontal.—a*) When Daubrée subjected to torsion narrow strips of glass, measuring about a yard in length, and produced on them the well-known system of intersecting fractures, he gave the science of geology one of its most impressive laboratory experiments and one of its most popular textbook illustrations on the subject of joints.

Careful analysis, however, reveals the fact that the conjugate systems of fractures which he produced, do not correspond directly to similar joint systems in nature. Figure 5 is a sketch of the fractures forming two prominent "fans" on one of Daubrée's plates.[1]

The tendency to form such "fans" is obvious in all torsion experiments made with glass. Duparc and LeRoyer found that it is the more pronounced, the thicker the glass plate is which is used for the experiment.[2]

[1] The one in the center of the plate reproduced on Plate XII of Haug, *Géologie*, Vol. I (Paris, 1911) (opp. p. 228).

[2] L. Duparc and A. LeRoyer, Contributions à l'étude expérimentale des diaclases produites par torsion," *Archives des Sciences phys. et nat.*, 3me sér. XXII (Genéve, 1889), p. 307. Daubrée used plates 7 mm. thick; on plates of 2 mm. thickness or less, "fans" may not form at all.

Each "fan" consists of a gently curved "master-joint," marked t and t', from which start, at a very acute angle, a number of minor joints, s and s', which unmistakably tend to be straight and parallel to each other.

The clue to this peculiar fan-structure of fractures we find in Hartmann's experiments with rectangular strips of soft steel.[1] Under torsion, two systems of Lüders' lines appeared on them, each parallel to one of the sides of the test piece, intersecting practically at right angles. This indicates that the direction of greatest tension traverses the surface obliquely, forming an angle near 45° with the axis of torsion.[2] When the deformation was carried farther additional lines of deformation appeared in the vicinity of the longer edges, bisecting the angles formed by the first set of lines.

When a plate is subjected to simple torsion, each element of the upper surface suffers simultaneously tension in one direction and compression at right angles to it. The same is true of the lower surface, but with the directions of tension and compression reversed.[3]

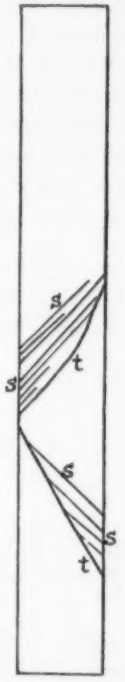

FIG. 5.—The fractures forming two characteristic "fans" on one of the glass plates used in Daubrée's experiments on fractures produced by torsion.

At any point on either surface, therefore, the position of the shearing planes is sharply defined through the combined action of tension and compression as shown diagrammatically in Figure 6. In case tension fractures are formed in addition, they bisect the acute angle of the shearing planes. This is what happened in Hartmann's experiment with

[1] Hartmann, *loc. cit.*, p. 175 and Fig. 173.

[2] This can be verified readily by drawing a circle on the flat side of a rubber eraser and twisting it. G. F. Becker, "The Torsional Theory of Joints," *Trans. Amer. Inst. Mech. Engineers*, Vol. XXIV (1895), p. 136.

[3] For the purposes of the following discussion it is important to remember that essentially horizontal tensional stresses arise in surfaces made convex, and similar compressive stresses in surfaces made concave through the process of bending.

strips of soft steel. The second set of fractures, formed after shearing was well under way along Lüders' lines, consisted of tension fractures, one started from the lower, the other from the upper surface.

Glass, on the other hand, being a highly brittle substance, in contrast to soft steel, will fail along tension fractures rather than along planes of shearing. The fractures marked *t* in Figure 5 are the only ones that form when the glass plate used in the experiment is very thin. They must, therefore, be tension cracks, one set produced on the under side, the other, symmetrical to it, on

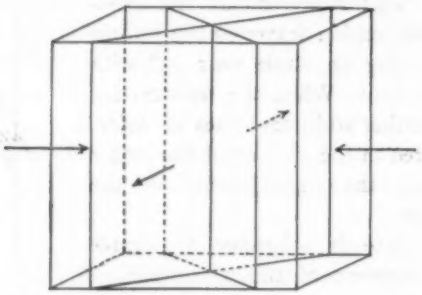

FIG. 6.—Diagram illustrating the position of the planes of shearing in a brittle body subjected simultaneously to compression and tension, both in a horizontal direction.

the upper surface, and both finally extended to both surfaces, owing to the thinness of the plate. The gentle curving of these cracks is quite in harmony with this interpretation.

The other set of fractures, marked *s* in Figure 5, intersects with the tension cracks at angles varying from 15° to 25°. This, however, is one-half of the angle of shearing characteristic of glass.[1]

The same angle for soft steel is approximately 45°. It is evident, therefore, that these fractures represent shearing planes produced by the compressive stress acting in the direction normal to the tensile stress. In the experiments made with glass, however, in contrast to those with mild steel, only one set of the shearing planes forms in connection with a tension crack, that only which

[1] To verify this, it is sufficient to compress small pieces of thick plate glass in a strong vise. The resulting angle of shearing can be measured conveniently by means of Penfield's contact goniometer.

lies favorable to the differential movement resulting from the process of torsion. Here, again, the fractures produced on the upper surface extend down to the lower surface and vice versa.

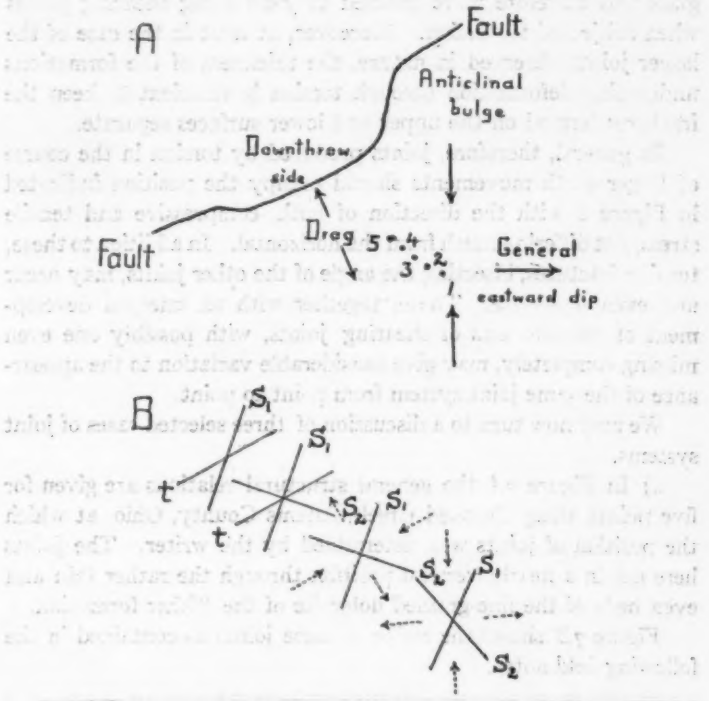

FIG. 7.—*A*. Map sketch, showing relation of stations on Crooked Creek, Adams County, Ohio, at which joints were measured, to the fault and to other structural features. *B*. Diagram showing the position of the joints observed at the stations 1, 2, 3, 4, 5. S_1 S_2=shearing joints; t=tension joints.

Since the intensity of the compressive stress increases with the thickness of the plate, it is evident that the fan-shaped groups of cracks will form the more freely the thicker the plate is.

The most striking feature of Daubrée's famous experiment, therefore, namely the formation of two systems of fractures intersecting approximately at right angles, is an accidental result of the exceptional brittleness of glass and the thinness of the plates

used, permitting the fractures produced on the upper and lower surfaces respectively to interpenetrate.

Most rock materials, on the other hand, are less brittle than glass and therefore more inclined to yield along shearing planes when subjected to torsion. Moreover, at least in the case of the larger joints observed in nature, the thickness of the formations undergoing deformation through torsion is sufficient to keep the fractures formed on the upper and lower surfaces separate.

In general, therefore, joints produced by torsion in the course of larger earth movements should occupy the position indicated in Figure 6 with the direction of both, compressive and tensile stress, not differing much from the horizontal. In addition to these, tension fractures, bisecting the angle of the other joints, may occur and even dominate. These, together with an unequal development of the two sets of shearing joints, with possibly one even missing completely, may give considerable variation to the appearance of the same joint system from point to point.

We may now turn to a discussion of three selected cases of joint systems.

a) In Figure 7*A* the general structural relations are given for five points along Crooked Creek, Adams County, Ohio, at which the position of joints was determined by the writer. The joints here cut in a nearly vertical position through the rather thin and even beds of the fine-grained dolomite of the Bisher formation.

Figure 7*B* shows the strike of these joints as contained in the following field notes.

Station	Set s_1	Set s_2	Set t
1.....	N 25 E strongly developed	N 40 W sharp and persistent	.....
2.....	N 20 E well developed	N 70 W (average) strong but variable	.....
3.....	N 20 E sharp and regular; closely spaced (2–10 in. apart)	N 70 W (average) few and far apart (several feet); irregular.	.....
4.....	N 22 E sharp and regular; (1–2 feet apart)	N 70 W very few, only three good joints seen	N 62 E sharp and regular, 1–2 feet apart
5.....	N 20 E sharp and regular	.....	N 65 E dominant system, closely spaced

The very regular systems of joints observed at station 1 obviously owe their existence chiefly to the compressive stress caused by the upward buckling of the strata farther north along the fault. The change of the angle of shearing from 65° at station 1, to 90° at stations 2 and 3, probably is due to factors which will be discussed in the second part of this paper. It is brought about by a shifting of the trend of the system s_2 which at the same time becomes more and more irregular and scattered. At station 4 set s_2 is only represented by a few widely separated cracks, while a new system of fractures makes its appearance. They are parallel to the fault and become increasingly prominent and closely spaced as the fault is approached. They must be tension cracks.

The joints at station 5 offer an exact analogy to the fan-shaped cracks formed on the upper surface of a glass plate under torsion, with shearing planes developed only on one side of a tension crack.

The great practical value of such an interpretation of joints, during the progress of field work, is obvious. In this case, for instance, the joints at stations 1 to 3 would lead the field geologist at once to look for an uplift either north or south of these points, or both. The sudden appearance and increasing importance of an additional system such as the joints of set t would suggest the neighborhood of a flexure or a fault not far to the northwest striking N 65 E.

Information such as this will certainly pay for the time spent on detailed intelligent observation.

b) The remarkable jointing exposed along the shores of Lake Cayuga and Lake Seneca, "resembling the gigantic ruins of Cyclopean architecture," has been made classic through the series of woodcuts published by Hall in 1843.[1]

Miss Pearl Sheldon[2] has given us a large number of careful measurements of these joints in the vicinity of Cayuga Lake. Two systems of joints stand out from all others. They are generally stronger, more regular, and remarkably constant in their

[1] *Geology of New York*, Pt. LV (Albany, 1843), pp. 303–6. For good modern illustrations see, e.g., *Watkins Glen-Catatonk Folio*, No. 169 (1909), Pl. I, Figs. 15 and 16; and *Jour. Geol.*, Vol. XX (1912), p. 78.

[2] Pearl Sheldon, "Some Observations and Experiments on Joint Planes," *Jour. Geol.*, Vol. XX (1912), pp. 53–79; 164–83.

trend. They are practically vertical. The strike of the one set ranges from N 70 E to N 80 E with the majority lying between N 75 E to N 78 E. The other set has a strike ranging from N 20 W to N 10 E. Frequently joints of the two extremes, near N 20 W and N 10 E, are present at the same locality.

No detailed data are given for the large number of minor joints of this region. Their trend seems to be highly variable, in general and from point to point, and ranges through all points of the compass. They are often curved and irregular, and as a rule small. They generally show a large hade, ranging as high as 60°.

The remarkably uniform position of the two major joint systems[1] stands in strong contrast to the highly variable dip of the limbs of the low anticlines and synclines formed by the rocks of the region, as shown on the geological map.[2] This contrast is especially striking, as Miss Sheldon points out herself, where the dip and strike of the rocks changes rapidly from point to point along the pitching end of an anticline (for instance, the Shurger Point anticline)[3], while the position of the joint planes remains unchanged.

It is evident, therefore, that the formation of these joint systems was independent of the folding and followed it.

Here, as on Crooked Creek, one system is quite constant in its trend, while the other varies in such a way as to form angles ranging from about 65° to 90° with it. We are, therefore, justified in the assumption that they represent planes of shearing produced by compression in a NE–SW direction under general conditions of torsion. To test this interpretation, we turn to the geological maps of Watkins Glen and Catatonk quadrangles.

West of Cayuga Lake, along the axis of the Watkins anticline, the contact of the Portage and Chemung formations is nearly level, varying between 1,480 and 1,560 feet above sea-level for a distance of over 18 miles. As it approaches the valley of Cayuga Inlet, it rises above 1,600 feet. East of Ithaca, in the same general

[1] See especially Figs. 6 and 7 of Miss Sheldon's paper.

[2] See *Watkins Glen-Catatonk Folio*, No. 169.

[3] *Loc. cit.*, p. 67.

direction, the contact rises rapidly to over 2,100 feet in a similar distance. A closer inspection of the northeast corner of Catatonk Quadrangle reveals the presence of considerable doming in the general direction suggested by the position of the joint planes. This broad anticlinal bulge does not seem to be mentioned in the text of the folio. The fact that the writer's attention was called to it through the analysis of the joints of Cayuga Lake, serves well to illustrate the practical possibilities of the method employed.

The presence of an uplift to the northeast accounts for the existence of a compressive stress in that direction. The horizontal tensile stress implied by the position of the joint planes can be accounted for equally well. Crossing the shores of Cayuga Lake in a southeasterly direction (suggested by the obtuse angle of the joints), we find that, on the crests of the Fir Tree Point, Watkins and Alpine anticlines, the contact of the Portage and Chemung formations remains essentially at an elevation between 1,600 and 1,700 feet above sea-level. Beyond the Alpine anticline, however, in the same southeasterly direction, within a similar distance, the same contact drops to near 1,000 feet in the vicinity of Jenksville in Newark Valley Township.

The existence of this depression in the direction suggested by the position of the joint planes, leaves little doubt that this relatively pronounced flexure gave rise to the tensile stress involved in the formation of the joints.

c) For a last example we turn to Thwaites's paper on the "Sandstones of the Wisconsin Coast of Lake Superior."[1]

When we plot the strike of the joints of this region as recorded in the table on page 96, it appears that the peninsula north of Washburn, including the Apostle Islands, in contrast to the regions to the west and south, is traversed by two dominant and persistent systems of major joints. One of the two strikes on the average E–W, the other about 10° east of north. Most probably they represent planes of shearing. The position of the acute angle points to the action of a compressive stress in a NE–SW direction, with a tensile stress acting in a NW–SE direction.

[1] F. T. Thwaites, "Sandstones of the Wisconsin Coast of Lake Superior," *Wis. Geol. and Nat. Hist. Sur., Bull. 25* (1912).

The map accompanying Thwaites's paper shows that the jointed area lies in the continuation of the northeastern end of the great Douglas thrust fault. If this fault had any horizontal component in the northeasterly direction, it could have supplied the compressive stress responsible for the position of the joints.

Unfortunately, the fault contact of the Middle Keweenawan traps with the underlying much younger Orienta sandstone was found exposed only at four localities. At three of these, the exposures were not even found sufficient to measure the hade of the thrust plane.[1]

In the vicinity of the falls of the Amnicon River, however, the fault-plane proper was found exposed at two separate localities, about 500 feet apart. Here, at both points, two systems of grooves were observed on slickensided surfaces in the immediate vicinity of the fault, on surfaces of conglomeratic beds of sandstone which represent most probably shreds of lower beds dragged up along the thrust-plane.[2] One of the sets of grooves "is parallel to the dip, the other is inclined at an angle of about 30° in a NE–SW direction."[3]

Although the grooves are not part of the fault-planes proper, but occur on what seem to be irregular fragments of sandstone wedged in front of the fault, their constancy on seemingly different planes at points 500 feet apart can hardly be looked on as due to purely local movements. They are more likely the direct result of the last movements along the major thrust-plane and essentially parallel to them.

If the joints in the vicinity of the Apostle Islands really owe their origin to the action of this pressure directed upward at an angle of about 30° toward the northeast, we should find evidence of it in the position of the joint planes themselves. According to the table on page 96 of Thwaites's paper the joints have the tendency to be vertical. From the text we learn, however, in addition that "many of the E–W joints are inclined, usually at a steep angle to the north."[4]

[1] F. T. Thwaites, *op. cit.*, pp. 66, 76, 80, 81. [2] *Ibid.*, p. 83.
[3] *Ibid.*, p. 78. [4] *Ibid.*, p. 94.

When we plot the attitude of these joints, using the stereographic projection as explained on page 10 of this paper, we find that the greatest (compressive) principal stress should have been directed upward from the southwest at an angle of 15° if we assume the E–W joints to dip 70° north, and of 30°, if they dip 50° north.

This correspondence is quite striking and leaves little doubt as to the correctness of this interpretation.

The northwest-southeast tension, indicated by the position of the obtuse angle of the joints in the Apostle Islands, is parallel to the gentle dip of the rocks of the Bayfield Group. Both dip and tension probably resulted from settling along the axis of the Lake Superior syncline simultaneous with the last movements along the thrust-plane.

d) The last two examples serve well to show how important it is that each observation of jointing be studied in its geographical and structural relations to all others. To assemble the joints observed over a large area in a single diagram means to veil their true relationships. A diagram, published by Hobbs in 1905,[1] shows the strike of 1,004 joints measured by Mr. C. G. Brown in the vicinity of Cayuga and Seneca lakes, New York. It clearly indicates the existence of two nearly orthogonal double systems of conjugate joints. A comparison with Miss Sheldon's diagram[2] shows that the earlier diagram represents a composite picture of the joint systems of two different localities, since the vicinity of Cayuga Lake exhibits only one of the two double systems, as described above.

A fine example of carefully recorded data giving definite measurements of strike and dip, and accurate geographical location of every joint measured, may be seen, for instance, in R. S. Tarr's field observations embodied in Shaler's "Geology of Cape Ann."[3]

3. *Greatest compression horizontal, least compression vertical.*— The position of the principal stresses and of the resulting planes

[1] W. H. Hobbs, "Examples of Joint-controlled Drainage from Wisconsin and New York," *Jour. Geol.*, Vol. XIII (1905), p. 370.

[2] *Loc. cit.*, p. 66.

[3] N. S. Shaler, "The Geology of Cape Ann, Massachusetts," *Ninth Ann. Rep., U.S.G.S.* (1889), pp. 597–602 and Pls. 72–74.

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[3] *Ibid.*, p. 78. [4] *Ibid.*, p. 94.

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This correspondence is quite striking and leaves little doubt as to the correctness of this interpretation.

The northwest-southeast tension, indicated by the position of the obtuse angle of the joints in the Apostle Islands, is parallel to the gentle dip of the rocks of the Bayfield Group. Both dip and tension probably resulted from settling along the axis of the Lake Superior syncline simultaneous with the last movements along the thrust-plane.

d) The last two examples serve well to show how important it is that each observation of jointing be studied in its geographical and structural relations to all others. To assemble the joints observed over a large area in a single diagram means to veil their true relationships. A diagram, published by Hobbs in 1905,[1] shows the strike of 1,004 joints measured by Mr. C. G. Brown in the vicinity of Cayuga and Seneca lakes, New York. It clearly indicates the existence of two nearly orthogonal double systems of conjugate joints. A comparison with Miss Sheldon's diagram[2] shows that the earlier diagram represents a composite picture of the joint systems of two different localities, since the vicinity of Cayuga Lake exhibits only one of the two double systems, as described above.

A fine example of carefully recorded data giving definite measurements of strike and dip, and accurate geographical location of every joint measured, may be seen, for instance, in R. S. Tarr's field observations embodied in Shaler's "Geology of Cape Ann."[3]

3. *Greatest compression horizontal, least compression vertical.*— The position of the principal stresses and of the resulting planes

[1] W. H. Hobbs, "Examples of Joint-controlled Drainage from Wisconsin and New York," *Jour. Geol.*, Vol. XIII (1905), p. 370.

[2] *Loc. cit.*, p. 66.

[3] N. S. Shaler, "The Geology of Cape Ann, Massachusetts," *Ninth Ann. Rep., U.S.G.S.* (1889), pp. 597–602 and Pls. 72–74.

of shearing for this grouping of stresses is represented diagrammatically in Figure 8; Figure 9 illustrates the occurrence of this type in nature on a small scale.[1] It shows "symmetrical faults" in a hard encrinal layer a foot or two in thickness in the Hamilton shales, exposed along the shores of Cayuga Lake. "The exposures of this layer along the lake show faults every few feet." "The strike of the majority is from 20–25° north of west." "Their inclination is sometimes south and sometimes north and the angles are nearly

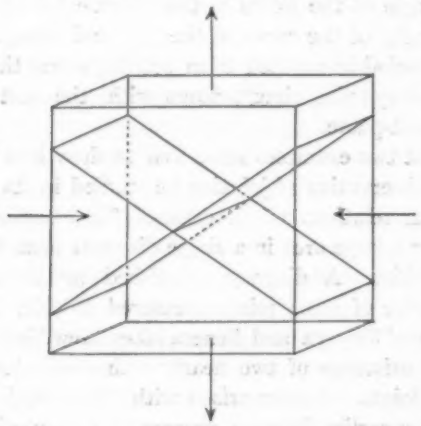
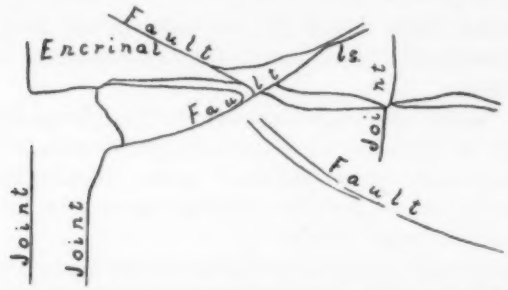


FIG. 8.—Diagram illustrating the position of the planes of shearing in a brittle body subjected to compression in a horizontal direction with the direction of easiest relief (least principal stress) vertical.

the same in the two cases, making the faults symmetrical about a nearly horizontal plane." "The hade varies from 45° to 75°, but most are near the average, which is 62°." The fault surfaces are slickensided and covered with strong, even striations. "The vertical displacement along these faults is from a fraction of an inch to three inches." The faults "usually continue for a few feet in the adjacent shale, but instead of continuing with the same hade, they flatten out and become nearly horizontal in the shales where no hard layer is present."[2]

[1] Pearl Sheldon, "Some Observations and Experiments on Joint Planes," *Jour. Geol.*, Vol. XX (1912), Fig. 3, p. 61.

[2] *Ibid.*, pp. 60–62.



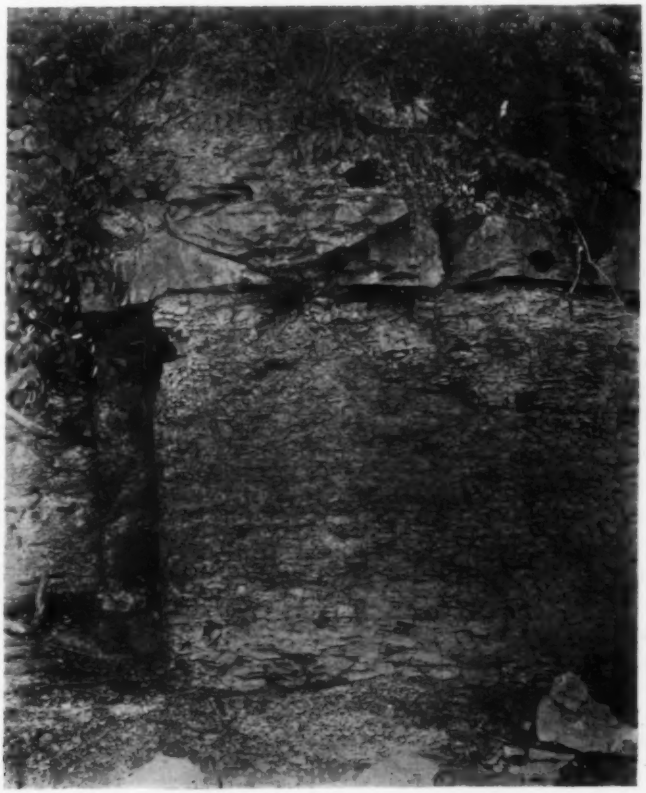


FIG. 9.—Planes of shearing due to stress relations similar to those illustrated in Fig. 9. Bed of hard encrinal limestone in Hamilton shales, exposed along shore of Cayuga Lake. (P. Sheldon, 1912.)

Horizontal faults "occur by the score in the shale beds," usually offsetting the vertical joints for distances often measuring several inches.

These "faults" are unquestionably shearing planes forming an acute angle of approximately 60° facing the direction of the horizontal compressive stress which is clearly manifested in the differential movement between adjoining layers of shale referred to above as "horizontal faults."

Identical results have been obtained in the laboratory, whenever sufficiently brittle materials were subjected to horizontal compression in the course of experiments on overthrusting,[1] and before our eye loom up the sections of the mountain ranges which these experiments were to help explain, with thrust faults in astonishing numbers and on gigantic scales.

Here the subject of our discussion assumes different proportions. We realize that the grouping of stresses resulting in the formation of any of the fracture systems discussed before remains the same whether the fracturing finally results in the formation of vast lines of displacement generally referred to as major faults, which may bound mountain ranges or even continents, or ends with the production of minute cracks which, filled with white calcite, form a delicate network on the dark rock and, found on the surface of flat pebbles on the wet beach, are the delight of children.

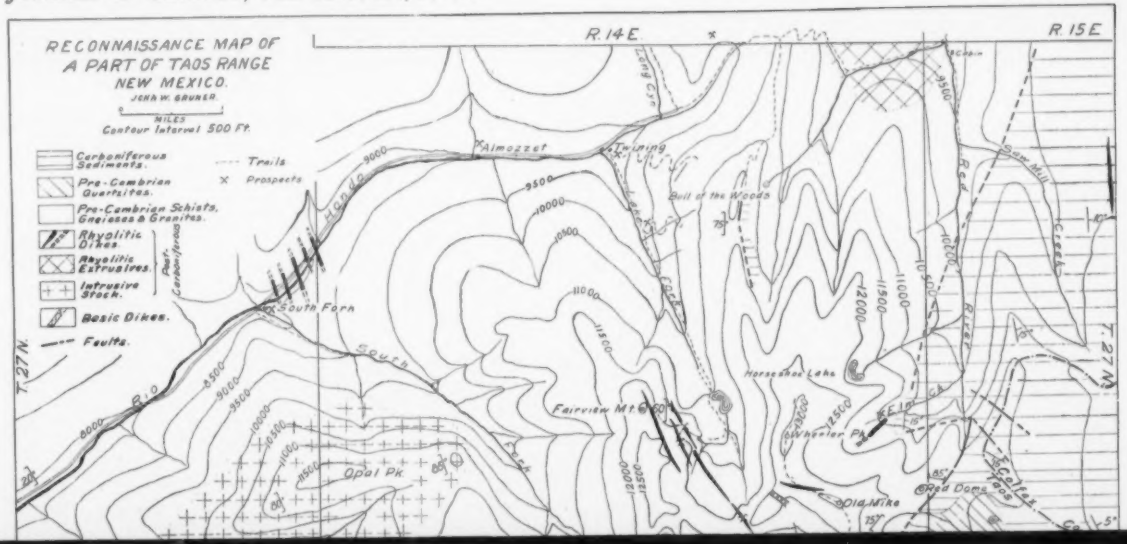
Before we can extend the application of Hartmann's law to the larger scale of the great overthrusts of folded mountains, we must first answer a question which now assumes fundamental importance: Is the angle of shear, in a given substance, sufficiently constant under widely different conditions of pressure and temperature so as to exclude the possibility of grave errors in its use?

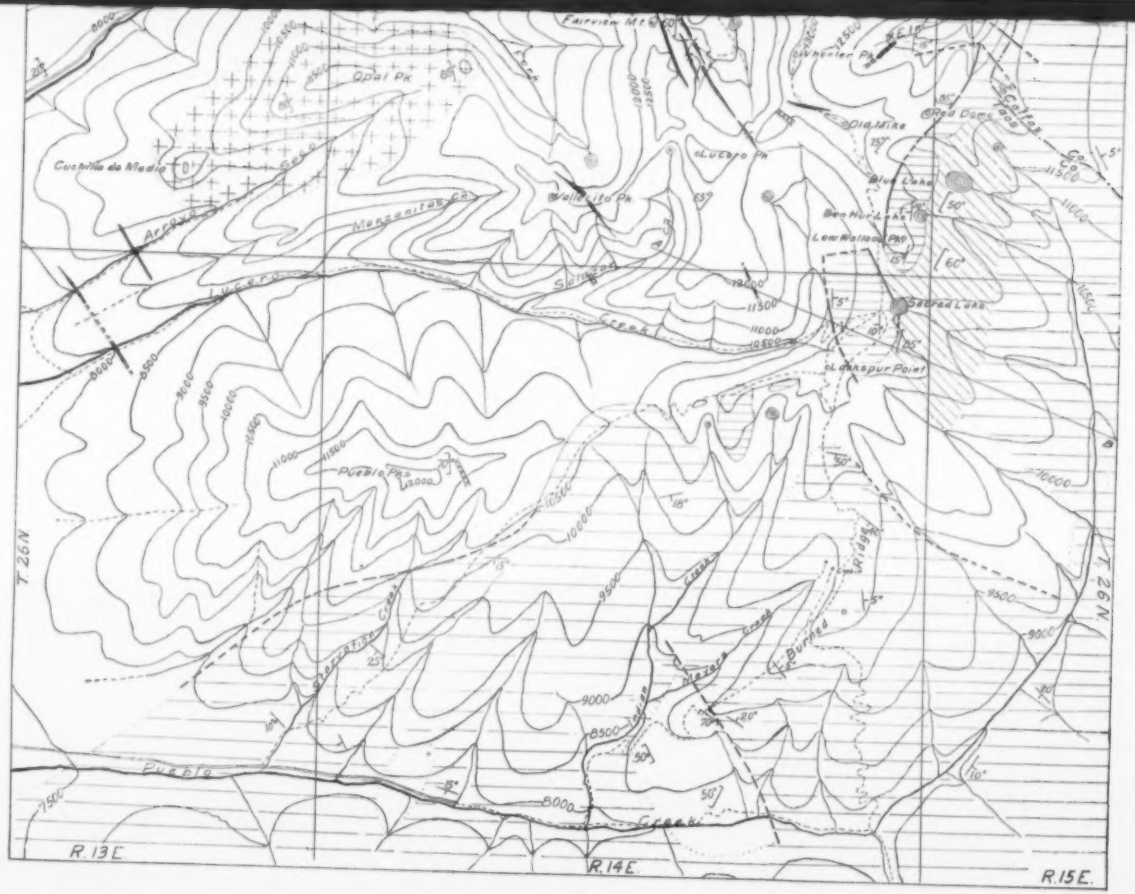
We may approach this question best by turning to the ingenious mathematical theory which Mohr has given to account for the results of Hartmann's and others' experiments.

[1] See, for instance, H. M. Cadell, "Experimental Researches in Mountain Building," *Trans. Roy. Soc. Edinburgh*, Vol. XXXV (1890), pp. 337–57; and R. T. Chamberlin and W. Z. Miller, "Low-Angle Faulting," *Jour. Geol.*, Vol. XXVI (1918), pp. 1–44, especially Fig. 9.

Note, however, that the position of the strain ellipsoids in the rigid layers in Fig. 10 does not correspond to the writer's interpretation.

[*To be continued*]


RECONNAISSANCE MAP OF A PART OF TAOS RANGE NEW MEXICO.
JOHN W. GRUNER.
MILES
Contour Interval 500 FT.
Carboniferous Sediments.
Pre-Cambrian Quartzites.
Pre-Cambrian Schists, Gneisses & Granites.
Rhyolitic Dikes.
Rhyolitic Extrusives.
Intrusive Stock.
Basic Dikes.
Faults.
Trails.
Prospects.
Pre-Carboniferous
R.14E.
R.15E.
T.27N.
T.27N.
Almozzet
Twining
Bull of the Woods
Horseshoe Lake
Fairview Mt.
Opal Pk.
Old Mike
Red Dome
Lobo Creek
Rio Hondo
South Fork
Rio Hondo
Red River
Cabresto Creek
Goat Mill
Cabresto Peak
Wheeler Pk.
9000
9500
10000
10500
11000
11500
12000
12500
13000
13500
14000
8000
8500


Fairview Mt.
Opal Pk
Cuchilla de Media
Arroyo
Manzanita Co
Manzanita Creek
Valle Lito Pk
El Cuervo Pk
Old Mine
Gold Dock
Gallop
Blue Lake
Bear Hurd Lake
Low Hollow Pass
Sanford Lake
El Ghanpur Point
Puebla Pk
Puebla
Puebla Creek
Manzanita Creek
Burned
Ridge
T. 26 N.
R. 13 E.
R. 14 E.
R. 15 E.

GEOLOGIC RECONNAISSANCE OF THE SOUTHERN PART OF THE TAOS RANGE, NEW MEXICO

JOHN W. GRUNER
University of Minnesota

INTRODUCTION

The Taos Range is a part of the Sangre de Cristo Range. Not more than about two-fifths of the Sangre de Cristo Range extends into New Mexico. The larger portion, the Culebra Range and the Sierra Blanca, lies in southern Colorado. Where the Culebra Range crosses the boundary line into New Mexico it splits into two great uplifts, the Taos Range and the Cimarron Range, which find their continuation in the Mora Range and Las Vegas Range respectively. The Taos Range proper is about 30 to 35 miles long and has an average width of 15 miles. Its northern limit is Costilla Creek, its southern Ferdinand Creek. The region described in this report is situated in north central New Mexico near the Colorado line. (See Fig. 1.)

The southern part of the Taos Range, as seen from the Rio Grande Valley to the west of it, offers an imposing view. From an altitude of about 7,000 feet, the elevation of the valley above sea-level, a number of peaks rise to snowy heights within a distance of a few miles. The mountain front is deeply incised by Pueblo Creek, Lucero Creek, and Rio Hondo, which flow westward to, the Rio Grande. (See topographic map, Plate XIII.)[1] The Red River (called "Colorado Creek" by Stevenson[2]), of which only a few miles are in the area mapped, has a northerly direction before it turns westward and breaks through the main chain of the mountains below Red River City.

[1] The attached topographic map was made by the writer who used as basis a map compiled by the United States Land Office and the United States Forest Service. The peak which is called Taos Peak by Stevenson is generally referred to as Wheeler Peak now.

[2] John J. Stevenson, "Report upon Geological Examinations in Southern Colorado and Northern New Mexico, 1878–1879," *Report U.S. Geog. Sur. West of the 100th Meridian*, Vol. 3, Supplement, 1881.

On the east of the Taos Range the broad Moreno Valley separates the Taos Range from the Cimarron Range, which is nearly as high. On this eastern slope of the range watercourses are rather scarce.

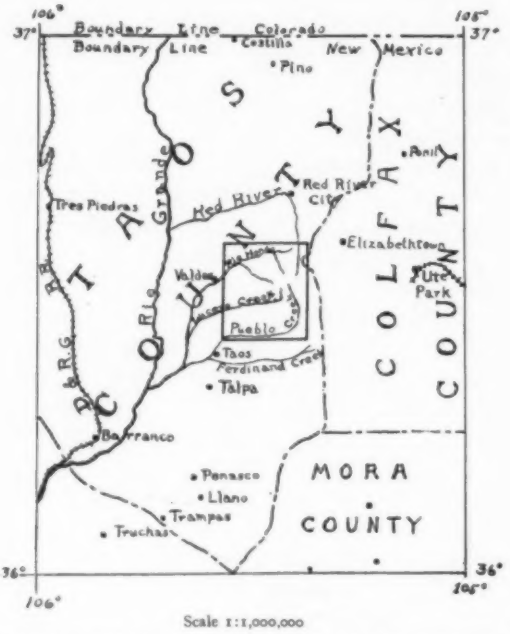


FIG. 1.—North central New Mexico showing location of area mapped. Copied from Plate I of *Professional Paper No. 68.*

DESCRIPTIVE GEOLOGY

The Taos Range is built up of three great rock systems. The pre-Cambrian gneisses, schists, and granites constitute the basement and greater part of the core of the uplift. Upper Carboniferous strata of great thickness are turned up on the east and south sides of the range. These older systems are intruded by stocks and dikes of granite and rhyolite porphyry respectively.

Along the western slope of the mountains large alluvial fans spread over the plains toward the Rio Grande for a number of miles,

where they are finally encroached upon by the basalt flows of the Rio Grande Valley.

In Stevenson's report[1] the mountains north and west of Pueblo Creek are assigned to the "Taos axis," those south and east of that creek to the "Mora axis." It was believed that the Taos axis does not continue beyond Pueblo Creek, but that a new one, the Mora axis, begins at the head of the Red River and runs southward, parallel to the Taos axis on the west, until the latter vanishes. No such structural division could be noticed by the writer between the Taos Range and Mora uplift south of it. The misconception was probably due to the belief that the Pennsylvanian strata exist also on the west side of the range.[2] The sedimentary outliers on the main range, to be described later, when viewed from the distance, easily give such an impression. No new axis begins in this district, but the Taos axis pitches steeply toward the south and the pre-Cambrian rocks disappear at the junction of Pueblo Creek and Indian Creek beneath the Pennsylvanian strata, which form here an uninterrupted anticline across the range.

In the region mapped this anticlinal structure is absent. No Pennsylvanian sediments were found on the western slope north of Pueblo Creek. The mountains present a bold fault scarp facing west. Whether sedimentary rocks of Pennsylvanian age underlie the thick débris fans and basalt flows or not is unknown at the present time. But farther north, in Colorado, Siebenthal mentions their occurrence on the west side of Culebra Peak and the anticlinal structure of the Sangre de Cristo Range at that latitude.[3]

PRE-CAMBRIAN CRYSTALLINE ROCKS

Ancient gneisses and schists.—The most ancient rocks are amphibolite and chlorite schists and gneisses that grade into greenstone in places. They cover the larger portion of the northwestern half of the area mapped, form an almost continuous outcrop along the western scarp of the range, and cap all of the high peaks with the exception of Old Mike. Lack of space will not permit to

[1] *Op. cit.*, pp. 41–42. [2] *Op. cit.*, p. 42.

[3] C. E. Siebenthal, "Geology and Water Resources of the San Luis Valley, Colo.," *U.S. Geol. Survey Water Supply Paper 240* (1907), p. 34.

describe these occurrences in detail, but as a rule sheeting in these rocks has a steep westerly to northwesterly dip. Nowhere in the ancient rocks were any close folds or signs of distortion and twisting seen, as might be expected in schists, and as were actually observed in the metamorphosed sedimentary rocks described below.

Granitic gneisses occupy a rather obscure position with respect to the more basic varieties, and may, in some cases, be of the same age as the batholithic granite intruding the older schists. In one instance, on Old Mike, this relationship was proved. Here the gneiss could be traced to its parent rock, the granite beneath.

The following outcrop deserves special attention in the opinion of the writer. The plateau south of Lucero Peak, between the Salazar and Lucero Canyon, is covered with a dark-green, fine-grained hornblendite and greenstone which resemble a flow. A "sheet" at least 200 to 300 feet thick, of dark, indistinctly schistose rock, overlies the granitic batholith. Ramifying apophyses from the granite beneath can be seen in the greenstone. Just north of Lew Wallace Peak lies a relatively small mass of greenish-gray, very fine-grained altered diabase. No cleavage or regular sheeting is visible in it. Whether this rock bears any genetic relation to the sheet on the opposite side of Lucero Canyon, just described, or not could not be determined.

Metamorphosed sedimentary rocks.—The metamorphosed pre-Cambrian sediments occupy belts of greatly varying width between the Pennsylvanian series on the southeast and the granite batholith on the northwest. The assumption that the batholithic granites are younger than the metamorphosed sediments is based upon the attitude of these formations, which flank and abut against the gneisses and granites. (See Fig. 2.) The formations are chiefly composed of quartzites and quartz and chlorite schists, and are undoubtedly of sedimentary origin.

The area of quartzite as outlined on the map claims accuracy only along the western margin. The eastern limit could only be estimated; therefore the outcrop may be somewhat narrower. The dip of the quartzite is steeply eastward, varying from 45° to 90°. Jointing at right angles to the beds is the rule. Figure 3 shows a nearly perpendicular exposure of quartzite, 300 feet high,

northeast of Ben Hur Lake. No trace of the bedding of the original sandstone was detected, perhaps due to the possible identity of the original bedding and the sheeting. The attitude and character of the quartzite strongly suggest this possibility to the writer. The color of the formation as a whole is yellow, but the southern end of it becomes reddish and purplish gray.

Southeast of Sacred Lake the very steeply dipping quartzite overlies a very much folded and twisted, thinly laminated chlorite schist. The foliation of the latter, as a whole, is parallel to that of quartzite. What appears to be a continuation of the quartzite

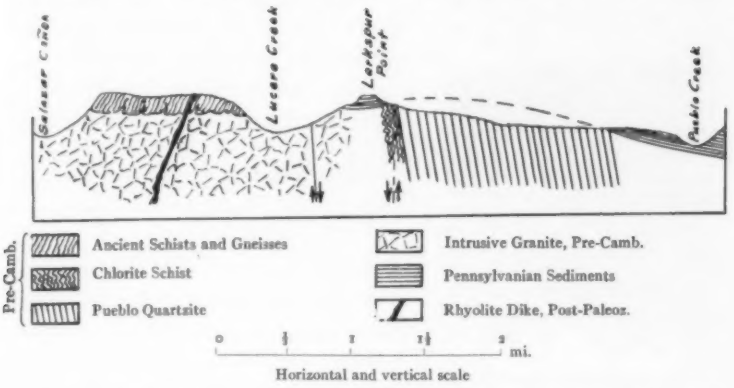


FIG. 2.—Cross-section from Salazar Canyon to Pueblo Creek, along line *A-B* on map.

and schist is seen half a mile southwest of this locality, just below Larkspur Point. Here steeply tilted chlorite epidote schist forms a cliff of conspicuous gray color. Strike and dip of the sheeting are very similar to that of the quartzite. Southwest of Pueblo Peak, adjacent to and north of the Pennsylvanian sediments, steeply inclined quartz-schist forms sharp craggy outcrops and cliffs. The formation flanks Pueblo Peak parallel to the fault line for an unknown distance toward the west.

Intrusive granites.—The distribution and composition of the granites suggest a close genetic connection between the individual areas. It is highly probable that all belong to one great batholith

which arched up the overlying formations and metamorphosed the sediments.

One of the largest exposures of this batholith is along the Rio Hondo, where a light-gray, very coarse biotite granite outcrops. It weathers easily and forms curiously shaped pinnacles in some places. Also along Lucero Creek a pinkish, more or less gneissoid, granite is found. The latter is also the predominating rock in the Salazar Canyon, and from here a broad belt of it passes beneath Lucero Peak to Old Mike.

FIG. 3.—Pueblo quartzite on Ben Hur Lake. Looking northeast. Unconformity on upper left. Pennsylvanian beds nearly at right angles to sheeting of quartzite.

The rocks from Old Mike and Red Dome show every gradation from a typical red granitic gneiss to a medium-grained biotite granite. Medium-grained biotite granite varying in color from pink to greenish gray also covers a large part of Red River Canyon, especially on the west side. A detailed examination was impossible in this part of the district.

Half a mile west of Larkspur Point pink medium to coarse-grained granite outcrops on the steep slope above Indian Creek. South of Larkspur Point the continuation of this outcrop is found in contact with remnants of ancient schist that caps a part of Larkspur Point. Farther toward the southeast the gneissoid granite is exposed along the northwestern tributary of Pueblo Creek for a distance of two and a half to three miles.

Basic dikes.—A number of basic dikes are intrusive into the granite of the batholith. Their age is probably pre-Cambrian. The most prominent one occurs just east of the highest point of Pueblo Peak and has a width of 100 to 150 feet. Its trend corresponds to that of the others, which have a northwest to southeast direction. In composition and texture it approaches a gabbro.

Two pre-Cambrian inliers that cannot be classified outcrop on Pueblo Creek. Quartz and mica schists and some amphibolite are the only rocks in these inliers seen by the writer.

CARBONIFEROUS SEDIMENTARY ROCKS

In the district mapped all sedimentary rocks belong to the Pennsylvanian series. Stevenson[1] described them as Carboniferous, attempting no further divisions then. Later writers, especially W. T. Lee,[2] who examined parts of this series farther east and north, recognized them as belonging to the Pennsylvanian series only. A number of fossils, collected by the present writer near the base of the sedimentary series, belong to the Pennsylvanian fauna. Six species were identified: *Lopophyllum profundum, Siminula subtilita, Spirifer cameratus, Spirifer rockymontanus, Productus cora, Productus semireticulatus.*

No generalizations concerning the thicknesses and divisions of the series can be given in this paper with the exception of the statement that by far the largest portion of the beds is composed of clastic material. The lowest member is usually a basal conglomerate grading into a sandstone, but in some localities limestone overlies directly the pre-Cambrian, and the sequence is reversed. It is very common to see a limestone in sharp contact with a coarse clastic in some places. On the other hand, formations hundreds of feet thick are found in which the transitions from one member into another are very gradual. Lithologically very similar beds of clastic material occur at many different horizons of the series and some of them are of such thickness that even considerable displacements by faults may be easily overlooked. The fact that all the faults seen by the writer in the sediments are normal and that evidence of folding due to lateral compression is absent seems to indicate that the Taos Range, if not the whole Sangre de Cristo Range, was formed solely by intrusive activity, probably in early Tertiary time.

[1] *Op. cit.*

[2] W. T. Lee, "Geology and Paleontology of Raton Mesa and Other Regions in Colorado and New Mexico," *Prof. Paper 101* (1918), pp. 41–42.

Distribution of the sediments.—The sedimentary rocks cover portions of the Pueblo Creek and Red River drainage basins, and extend far beyond the southern and eastern margins of the area mapped. While the thickness of the formations may be estimated at several thousand feet, at least 2,500 feet in the southeast corner of the district, erosion has reduced the thickness of the sediments toward the northwest to less than 300 feet above Sacred Lake.

The contact of the sediments with the pre-Cambrian rocks follows approximately a line from the southwest corner of the quadrangle to a point on Starvation Creek, about 1 mile south of Pueblo Peak. A normal fault of unknown displacement, probably relatively small, has sharply upturned the sandstones and limestones against quartz-chlorite schists west of Starvation Creek. Here at the bottom of the creek 100± feet of dense gray non-fossiliferous limestone are seen the base of which is not exposed. On it rests a dense, brownish-gray, arkosic sandstone that is brownish red when weathered. This rock caps most of the ridges and is of great thickness.

Farther east, on the high divide between Pueblo Creek and Lucero Creek, the foregoing limestone is overlain by a greenish-gray calcareous and arkosic grit. This grit is of wide extent and great thickness, not only in this district, but beyond its limits. At certain horizons this rock is replete with fossil fragments, especially crinoid stems. It becomes gradually coarser toward the top of the formation and changes to a conglomerate which contains subangular pebbles of quartz, gneiss, granite, and schist. They do not exceed a diameter of 1 inch, but attain greater dimensions on Burned Ridge.

About 1½ miles south of Larkspur Point, where the strata rest on pink granite, the beds dip steeply soutwestward. The basal conglomerate clearly derived from the pre-Cambrian rocks beneath grades into sandstones, grits, and conglomerates. They are of great thickness and constitute no definite, sharply separated members. The attitude of the beds in connection with the dip of the same formation in the opposite direction on the southwest slope of Burned Ridge, near a point where a fault crosses Meyer's Creek, indicates a synclinal structure whose axis runs at right angles to Burned Ridge and pitches southeast.

At the head of Pueblo Creek the Pennsylvanian rests on pre-Cambrian quartzite. A north-south fault crosses the divide between Red River and Pueblo Creek, bringing the sandstones and grits into juxtaposition to the granite on the west. A little farther north two minor step faults cross the ridge from northwest to southeast. North of this exposure the sedimentary rocks are confined almost entirely to the area east of Red River. The river has cut a deep canyon into the sedimentaries, exposing on the east slope a thickness of nearly 1,000 feet of the Pennsylvanian. About 200 feet above the creek bottom the following approximate section is exposed:

	Feet
Red sandstone, very fine grained	100–150
Arkosic, light-colored sandstone, at least	200
Gray, fossiliferous limestone	50±
Dark-gray shale, carbonaceous in places	50±
Light-gray quartz conglomerate	40±
Concealed base	.....

A number of outliers of the Pennsylvanian are situated on the east slope of the main range and extend from Bull of the Woods to the head of Indian Creek. The most interesting outlier, a block faulted down on at least three of its four sides, lies east of Larkspur Point. (See Fig. 2.) A partial section of it measured just south of Sacred Lake is given below:

	Feet
15. Light-gray, very hard and massive arkosic sandstone	15
14. Brownish-gray, shaly limestone	30
13. Lime cemented conglomerate (description below)	20
12. Puddingstone conglomerate	10
11. Dark-red, very dense shale	20
10. Light-gray arkosic sandstone	12
9. Puddingstone conglomerate	25
8. Gray, massive, argillaceous limestone	45
7. Light-brown, medium-grained calcareous grit	20
6. Grayish-green shale, non-laminated	6
5. Puddingstone conglomerate (very coarse)	25
4. Brownish-gray, gritty limestone, fossiliferous	21
3. Red shale, somewhat arenaceous	9
2. Puddingstone conglomerate (extremely coarse)	32
1. Dark-red, very dense, massive shale	15+
	305

Concealed base about 50+ feet above schist

Of special interest in the outlier are the five members listed as puddingstone conglomerates on account of their unusual texture and composition. Their color as a whole is dark red. Joints and bedding planes are few and far apart in the three lower members. The lowest one (No. 2) of the formation consists of very angular "pebbles" and platy fragments of green chlorite and gray quartz-schist and gray slate, varying in size from mere sand grains to great bowlders 3 to 4 feet in diameter. They are imbedded in a red argillaceous and arenaceous cement, which makes up 80 to 85 per cent of the volume of the conglomerate. The highest member of the conglomerates (No. 13) which contains pebbles not exceeding 1 inch in diameter has only calcite as cement, which contains abundant fossil fragments.

FIG. 4.—Opal Peak. Looking northeast. Center of porphyry stock with nearly vertical sheeting.

POST-PALEOZOIC IGNEOUS ROCKS

Though outcropping in areas 5 to 7 miles apart, the Red River rhyolite flow, the intrusive Opal Peak porphyry, and the numerous rhyolitic dikes are chemically and mineralogically much alike and probably of the same age. They are certainly post-Carboniferous, for one of the dikes cuts the Pennsylvanian beds on the divide east of Red River.

Only a part of the thick rhyolite porphyry flow on Red River lies in the area mapped. The rock is light gray in color. The white porphyry of the extremely rugged Opal Peak and Cuchilla de Media lying between the darker gneisses and granites offers a conspicuous color contrast. The porphyry in spite of its prominent sheeting (Fig. 4) is very soft, and no dark minerals were seen in it.

The scattered white rhyolite porphyry dikes, intrusive into the pre-Cambrian rocks, as a rule have a northwesterly trend and steep or vertical dip.

GEOLOGICAL HISTORY

While the pre-Cambrian history of the Taos Range must necessarily remain rather obscure until further investigation and correlation with other regions, some of the events may be enumerated with more or less accuracy. Nothing is known about the origin of the ancient gneisses and schists. During the long erosion interval that exposed them and probably reduced the ancient mountains to base level, thick clastic deposits accumulated along the eastern and southern margins of the area now occupied by the granite batholith.

Upon this time of great erosion a period of intense orogenic movement followed, probably accompanied or closely succeeded by the intrusion of enormous volumes of granitic magma into the overlying schists, gneisses, and sediments. Later a number of basic dikes pushed their way into this batholith. No record of the geologic events that followed is preserved until Pennsylvanian time.

At the beginning of this period the present site of the range most likely formed the eastern shore of a considerable land mass west and northwest of it. Siebenthal, in his study of the San Luis Valley, has come to the same conclusion.[1] The very coarse and angular basal conglomerates of the Pennsylvanian leave no doubt as to the near-shore conditions that existed during their formation. The deposition of the puddingstone conglomerates and breccia and such bowlder beds (some bowlders with a diameter of 25 to 50 feet) as S. F. Emmons mentions farther north, on the east side of the Sangre de Cristo Range,[2] can have been brought about only by talus and wash from a precipitous coast directly into deep or quiet water. The fact that the pebbles of all conglomerates consist of pre-Cambrian schists, gneisses, quartzites, and granites suggests a land surface composed chiefly of these rocks. The enormous thickness of the strata leads also to the conclusion that a gradual sinking of the coast and progressive submergence from the east to the west took place during this period.

[1] C. E. Siebenthal, "Geology and Water Resources of the San Luis Valley, Colo.," *U.S. Geol. Survey Water Supply Paper 240* (1907), pp. 50–51.

[2] S. F. Emmons, "Orographic Movements in the Rocky Mountains," *Geol. Soc. Amer. Bull.*, Vol. I, pp. 245–86.

A more difficult problem arises from the question when deposition of sediments ceased. Stevenson speaks of the Jura Trias "Red Beds" that occur farther east and south as resting conformably upon the Carboniferous.[1] Lee, on the other hand, would rather assign them, at least partly, to the Pennsylvanian system.[2] He also favors the assumption that during Cretaceous time the sea covered practically all of the territory now occupied by the southern Rocky Mountains.[3] Until further evidence is found to prove that this view is correct, the present writer is inclined to believe that the site of the Taos Range proper during the Cretaceous was not, or only for a short epoch, an area of deposition for the reason that no Cretaceous sediments have been discovered on the west side of the Culebra and Mora ranges as far as can be learned from the available literature.

Probably during early Tertiary, deep-seated intrusive activity resulted in the uplift of the Sangre de Cristo Range. Since that time erosion has been at work continually. Glaciation in recent time has been an especially powerful agent in the process of destruction of the mountains.

ECONOMIC GEOLOGY

It is not likely that this district will ever attain great importance on account of its mineral resources. Three deserted camps on the Rio Hondo tell of an attempt to extract gold at South Fork and Almozzet, and copper at Twining. Lindgren has described these occurrences.[4]

A number of short prospect tunnels are situated in and close to some of the rhyolite dikes near Fairview Mountain and Lucero Peak where pyritization has altered the schist. Another claim is at the head of Elm Creek, near the base of the Pennsylvanian, where a narrow vein of barite and galena outcrops in the sediments.

[1] *Op. cit.*, p. 85.

[2] *Op. cit.*, p. 39.

[3] W. T. Lee, "Relation of the Cretaceous Formations to the Rocky Mountains in Colorado and New Mexico," *U.S. Geol. Survey Prof. Paper 96* (1916), p. 40.

[4] W. Lindgren and L. C. Graton, "The Ore Deposits of New Mexico," *U.S. Geol. Survey Prof. Paper 68* (1910), p. 83.

SUMMARIES OF PRE-CAMBRIAN LITERATURE OF NORTH AMERICA

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III. QUEBEC

THE EASTERN PART OF CANADA, NEWFOUNDLAND, AND GREENLAND

Recent studies of the pre-Cambrian in Nova Scotia and Newfoundland have been of a reconnaissance nature and do not modify earlier stratigraphic studies in any important way. In northern Quebec, Cooke, Wilson, and Tanton have extended reconnaissance mapping to new areas. Moore has studied the Belcher Islands of James Bay and finds a series of slates, graywackes, quartzites, limestones, and sandstones similar to the Nastapoka and Richmond groups described by Leith and Low. In northern Quebec, the succession from the base upward includes mainly (1) basic lavas, ferruginous dolomites, iron formations, rhyolites, other volcanics of the Keewatin type, etc.; (2) crystalline limestones, etc., of the Grenville type; (3) intrusives of granite and granite gneiss. In western Quebec, Timiskaming County, rocks of the preceding type are unconformably overlain by conglomerates and other poorly sorted clastics. The youngest rocks are basic intrusives. The sections made do not all agree as to the relative position of the Grenville and Keewatin types.

Buddington[1] finds that the Algonkian rocks of southeastern Newfoundland include 16,000 feet of sediments intruded by granite, syenite, and gabbro, basic and acid dikes and flows. The sediments consist of green and purple cherty slate, volcanic conglomerate, and upper series 6,000 to 7,000 feet thick of red and green sandstones, conglomerates, and shales, containing fresh feldspars, cross-bedding, and intra-formational conglomerates. The upper sediments show evidence of continental origin.

[1] A. F. Buddington, "Reconnaissance of the Algonkian Rocks of Southeast Newfoundland" (Abstract), *Bull. Geol. Soc. Am.*, Vol. XXV, No. 1 (1914), p. 40.

Buddington[1] studies the petrography and origin of the pre-Cambrian rocks of Newfoundland.

Cooke[2] says that the underlying rocks of the region at the head waters of the Broadback River in northwestern Quebec include a complex of basic schists, which is overlain unconformably by sediments including mica quartz schists, quartzites, arkose, and conglomerate. The youngest rocks are intrusive granites.

Cooke[3] states that the pre-Cambrian rocks of the northwestern part of Quebec are probably all pre-Huronian, using the latter term in the sense of the International Committee. The succession is as follows:

Mattagami series—In scattered patches
Unconformity
Nemenjish series—Seems to correspond to Grenville series farther south
Abitibi series—Basic lavas probably the equivalent of the Keewatin

Dresser[4] reports on an area along the south shore of Lake St. John about 120 miles north of the city of Quebec. Here are notable outliers of Paleozoic rocks preserved by faulting. The pre-Cambrian rocks of the area include granites and anorthosite, the latter containing important titaniferous magnetic ores.

Faribault[5] reports that the pre-Cambrian rocks of the Pleasant River Barrens, Lunenberg County, Nova Scotia, comprise the Goldenville quartzite which is overlain by the Halifax slates.

According to Faribault[6] the pre-Cambrian rocks underlying the Port Mouton map area comprise the Goldenville quartzite

[1] A. F. Buddington, "Pre-Cambrian Rocks of Southeast Newfoundland," *Jour. Geol.*, Vol. XXVII (1919), pp. 449–79.

[2] H. C. Cooke, "An Exploration of the Headwaters of the Broadback or Little Nottaway River, Northwestern Quebec," *Canada Geol. Surv. Summ. Rept. 1912* (1914), pp. 337–41, map.

[3] H. C. Cooke, "Some Stratigraphic and Structural Features of the Pre-Cambrian of Northern Quebec," *Jour. Geol.*, Vol. XXVII (1919), pp. 65–78, 180–203, 263–75.

[4] John A. Dresser, "Part of the District of Lake St. John, Quebec," *Canada Geol. Surv. Mem. No. 92* (1916), 88 pp., 5 pls., 2 figs., map.

[5] E. R. Faribault, "Geology of the Gold District of Pleasant River Barrens, Lunenberg County, Nova Scotia," *Canada Geol. Surv. Summ. Rept. 1913* (1914), pp. 259–63, map.

[6] E. R. Faribault, "Geology of the Port Mouton Map Area, Queens County, Nova Scotia," *Canada Geol. Surv. Summ. Rept. 1913* (1914), pp. 251–58.

18,348 feet in thickness and the Halifax slates 11,700 feet thick which overlie it.

Hovey[1] states that Archean gneisses appear on Parker Snow Bay, Greenland. They are overlain by Huronian quartzites, quartz schists, etc.

Malcolm[2] reports that the gold fields of Nova Scotia occupy the eastern half of the province bordering the coast. The oldest rocks are either Cambrian or pre-Cambrian sediments consisting of the Goldenville quartzites 16,000 feet thick conformably overlain by the Halifax slate 14,500 feet thick. Unconformably overlying them are Devonian or Carboniferous sediments. The quartzites and slates are thrown into folds having an east to west trend. Locally they are altered into gneisses and schists by a granite intrusion.

Moore[3] finds over 9,000 feet of pre-Cambrian sediments on Belcher Islands about seventy miles from the south coast of Hudson Bay. These sediments resemble the Nastapoka and Richmond groups described by Leith and Low. The sediments include iron formation, concretionary limestone, and dolomite, various slates, some of which show marked banding, quartzites, graywackes, and sandstones. The iron formation consists of jaspilite, chert, cherty-iron carbonate, green granules probably iron silicate, hematite, magnetite, and shale. Diabase sills and basalt flows of uncertain age are associated with the sediments. Moore concludes from his study of the concretionary structures of the limestones and the granular structures of the iron formations that they were formed in part by algae and other lowly organism. The chief source of the iron solutions, he believes, was lateritic weathering.

[1] E. O. Hovey, "Notes on Geology of the Region of Parker Snow Bay," *Bull. Geol. Soc. Am.*, Vol. XXIX (1918), p. 98.

[2] Wyatt Malcolm, "Gold Fields of Nova Scotia," *Canada Geol. Surv. Mem. No. 20* (1912), 331 pp., 42 pls., 24 figs., 2 maps.

[3] E. S. Moore, "The Iron Formation on Belcher Islands, Hudson Bay with Special Reference to Its Origin and Its Associated Algal Limestones," *Jour. Geol.*, Vol. XXVI (1918), pp. 412–38, 18 figs.

Tanton[1] maps and describes an area northeast of Lake Abitibi. His succession of pre-Cambrian rocks follows.

Post batholithic intrusives
  Olivine diabase
Keweenawan
  Quartz diabase, minette
Batholithic intrusives
  Granite and granite gneiss
Laurentian
  Igneous contact
Harricanaw series
  Arkose, conglomerate, graywacke
  Unconformity
Abitibi group
  Ferruginous dolomites and iron formation rhyolites, basalt, other volcanics, etc.

The Kewagama Lake area described by Morley E. Wilson[2] includes about eighty square miles bordering on the Province of Ontario. Cobalt is about thirty miles south of the southwest corner of the area.

The region is a peneplain whose elevation above sea-level varies from 900 to 1,100 feet. The divide between the James basin and the St. Lawrence system crosses it along a sinuous east and west line. Many of the low hills and streams of the region are parallel with the rock structure, most of which trends north of east. Some of the streams and lakes, however, have a strikingly linear north and south direction. Wilson believes that they follow preglacial depressions.

The bed rocks are all pre-Cambrian. In many places they are covered by stratified and unstratified glacial deposits and by postglacial, finely stratified lake clays and sands. Wilson classifies the pre-Cambrian rocks into two main divisions, but refrains from correlating them with any of the units recognized by the International Committee.

The oldest division consists of highly metamorphosed and folded rocks intruded by batholiths of granite and granite gneiss.

[1] T. L. Tanton, "The Harricanaw Turgeon Basin, Northern Quebec," *Canada Geol. Surv. Mem. No. 109* (1919), 84 pp., 1 map, 9 pls., 2 figs.

[2] Morley E. Wilson, "Kewagama Lake Map Area, Quebec," *Canada Geol. Surv. Mem. No. 39* (1913), pp. 39–122, 24 pls., 9 figs., map in pocket.

The intrusive granites and granite gneisses resemble the Laurentian. They intrude the Abitibi group. The latter include a volcanic complex, consisting of amphibolites and schists, chloritic rocks, slate, and ferruginous dolomite; and the Pontiac series of fine-grained mica schists and gneiss, hornblende schist, amphibolite, arkose, graywacke, and conglomerate.

This old complex is beveled by a pre-Cambrian peneplain above which lies the Cobalt series. The contact is sharp in places; in others it is gradational. The Cobalt series consists of two tillite-like conglomerates separated by even-bedded graywacke, argillite, quartzite, and arkose. The conglomerates are believed by Wilson to be glacial because of their heterogeneous character, their great extent, the size of some of the constituent bowlders, the distance of some of the bowlders from the parent ledge, the soled and striated nature of some of the bowlders, the improbability that the large bowlders could have been deposited from checked torrential streams, since they rest on a peneplained surface on which streams must have had a low gradient. The stratified deposits separating the conglomerates are believed by him to be of interglacial, lacustrine origin.

The Cobalt series are intruded by a mass of syenite porphyry classed as doubtfully Keweenawan. Considered as doubtfully of the same age are certain diabase dikes which cut the old complex, but are not known to intrude the Cobalt series. They are called the Nipissing diabase because of their lithologic similarity to the Nipissing diabase of the Cobalt district.

Wilson[1] presents a map and report on Timiskaming County, Quebec. An outline of his classification of the pre-Cambrian rocks follows.

Keweenawan—Basic intrusives
Huronian—Cobalt series
    Conglomerate
    Arkose
    Graywacke and Argillite
  Unconformity

[1] Morley E. Wilson, "Timiskaming County, Quebec," *Canada Geol. Surv. Mem. No. 103* (1918), 196 pp., 1 map. 16 pls., 6 figs.

Basal complex
- Pre-Huronian—Batholithic intrusions, granites, etc.
- Abitibi group
  - Pontiac series—Sedimentary schists, iron formation, etc.
  - Igneous intrusives—Chiefly basic
  - Extrusives—Chiefly basic
- Grenville series
  - Crystalline limestone, etc.

As in certain other recent papers by Wilson, he argues for a local nomenclature of the pre-Cambrian and against extensive correlations.

Wilson[1] reports that the succession of rocks underlying a part of Amherst Township of Quebec about 60 miles northeast of Ottawa, is as follows.

Late pre-Cambrian—A single diabase dike
Basal complex—
- Batholithic granite and syenite gneiss
- Buckingham series of intrusives—Gabbro, pyroxene, syenite, anorthosite
- Grenville series—Limestone, garnet, gneiss and quartzite

Wilson[2] reports on a geological reconnaissance of a part of northwestern Quebec. The region includes a southern limestone belt, Grenville series, a northern sedimentary and volcanic belt (Abitibi group), and an intermediate belt of banded gneisses largely igneous intrusives into the Abitibi group. The Abitibi group includes schists, iron formations, and conglomerates which have not been stratigraphically separated.

Wilson[3] concludes that the banded Laurentian gneisses are mostly of igneous origin and owe their banding to differentiation under deformative conditions, the latter causing fractures in the crystallized portions which become filled with magma.

[1] Morley E. Wilson, "Geology and Mineral Deposits of a Part of Amherst Township, Quebec." *Canada Geol. Surv. Mem. No. 113* (1919), 54 pp., 1 map, 17 pls., 3 figs.

[2] Morley E. Wilson, "A Geological Reconnaissance from Lake Kipawa via Grand Lake Victoria to Kawikawinika Island, Bell River, Quebec," *Canada Geol. Surv. Summ. Rept. 1912* (1914), pp. 315–36, fig.

[3] Morley E. Wilson, "The Banded Gneisses of the Laurentian Highlands of Canada," *Am. Jour. Sci.*, 4th Ser., Vol. XXXVI (1914), pp. 109–22.

Wright[1] says that the pre-Carboniferous rocks of the Clyburn Valley, Cape Breton, consist of a bedded series of volcanics invaded by quartz diorite and granite batholiths and by sills and dikes of basic materials.

IV. MANITOBA, SASKATCHEWAN, AND NORTHWEST TERRITORIES

Alcock[2] has made a reconnaissance of the Lower Churchill River region of Manitoba and reports that the pre-Cambrian rocks of the area include the following:

Pre-Cambrian	Granite and gneiss	Biotite granite gneiss, hornblende granite gneiss, amphibolite, granodiorite, porphyritic granite
	Churchill quartzite	Dominantly a dark gray, fine-grained quartzite
	Keewatin	Local areas of chloritic and sericitic schists

Bruce[3] has mapped and described the Amisk-Athapapuskow Lake area on the western border of the Canadian Shield on the boundary line between Saskatchewan and Manitoba. His succession follows:

		Kaminis granite Granite gneiss Hybrid granitic rocks
	Intrusive contact	
Upper Missi series	Arkose Conglomerate	
	Unconformity	
Lower Missi series	Slate Graywacke Quartzite Conglomerate	
	Unconformity	
	Cliff Lake granite porphyry	
	Intrusive contact	
Kisseynew gneisses Amisk series	Sedimentary and igneous gneisses and schists, lavas, tuffs, agglomerates, and derived schists	

[1] W. J. Wright, "Geology of Clyburn Valley, Cape Breton Island (Nova Scotia)," *Canada Geol. Surv. Summ. Rept. 1913* (1914), pp. 270–83, map, diagram.

[2] F. J. Alcock, "Lower Churchill River Region, Manitoba," *Canada Geol. Surv. Summ. Rept. 1915* (1916), pp. 133–36.

[3] E. S. Bruce, "Amisk-Athapapuskow Lake District," *Canada Geol. Surv. Mem. No. 105* (1918), 91 pp., map, 7 pls., 4 figs.

Camsell[1] reports on the results of a reconnaissance of a portion of the northwest territories between longitudes 108°30′ to 114°30′ and latitudes 58°30′ to 61°30′. His classification of the pre-Cambrian rocks of the area follows.

Athabaska sandstone (sandstone and conglomerate)
Unconformity
Granite and gneiss
Intrusive contact
Tazin series (mica, chlorite, and quartz schists, slates and limestone)

Camsell and Malcolm[2] present a reconnaissance map and report of the Mackensie River basin between longitude 100° to 135° and latitudes 55° to 68°. Pre-Cambrian rocks occur along the eastern border of the basin. Their classification of the succession follows.

Late pre-Cambrian	Sandstone, limestone, and basic flows and intrusives
Unconformity	
Granite and gneisses	
Intrusive contact	
Early pre-Cambrian	Schists, slates, limestones, and quartzites

McInnes[3] reports on a reconnaissance of 220,000 square miles lying between 91° to 106° longitude and 53° to 59° latitude. The area extends from Lake Winnipeg to Fort Churchill on Hudson Bay eastward to Prince Albert. The area is underlain chiefly by pre-Cambrian rocks excepting on the southwest corner, which is underlain by Cretaceous. Most of the pre-Cambrian rocks resemble the Laurentian of the Lake Superior region. In the eastern portion are found patches of the Keewatin and Grenville type. Sandstones like the Keweenawan of Lake Superior are abundant in the northwest part of the area. The classification of the pre-Cambrian by McInnes follows.

Keweenawan?	Athabasca sandstone—White and dull red, coarsely granular, siliceous sandstone and conglomerate in thick, horizontal beds

[1] Charles Camsell, "An Exploration of the Tazin and Taltson Rivers, Northwest Territories," *Canada Geol. Surv. Mem. No. 84* (1916), 124 pp., 18 pls., 1 map.

[2] Charles Camsell and Wyatt Malcolm, "The Mackensie River Basin," *Canada Geol. Surv. Mem. No. 108*, 154 pp., 1 map, 14 pls.

[3] William McInnes, "The Basins of Nelson and Churchill Rivers," *Canada Geol. Surv. Mem. No. 30* (1913), 146 pp., 19 pls., 1 map.

Laurentian	Biotite granite gneiss, hornblende gneiss, amphibolite, granodiorite, etc.
Grenville? (Lac La Ronge series)	Quartz diorites, pyroxenites, amphibolites, gneisses, and schists, and crystalline limestones
Keewatin	Chloritic and hornblende schists, diorites, hornblendites, serpentines, etc.
Igneous	Granites, pegmatites, diorite, dikes, younger than Laurentian

The pre-Cambrian[1] rocks east of the south end of Lake Winnipeg are provisionally classified as:

Post Lower Huronian	Manigolagan granite, Pegmatite and gneiss
Huronian	Wanigow series; conglomerate containing quartz, rhyolite granite, felsite, greenstone, jasper, and chert, maximum diameter of pebbles 1 foot
Keewatin	Arkose, graywacke, chert, jasper, gray gneiss, and schist
	Rice Lake series; greenstone, quartz porphyry, rhyobite, trachyte felsite, green and gray schist

[1] E. S. Moore, "Region East of the South End of Lake Winnipeg (Manitoba)," *Canada Geol. Surv. Summ. Rept. 1912* (1914), pp. 262–70, map.

[*To be continued*]

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